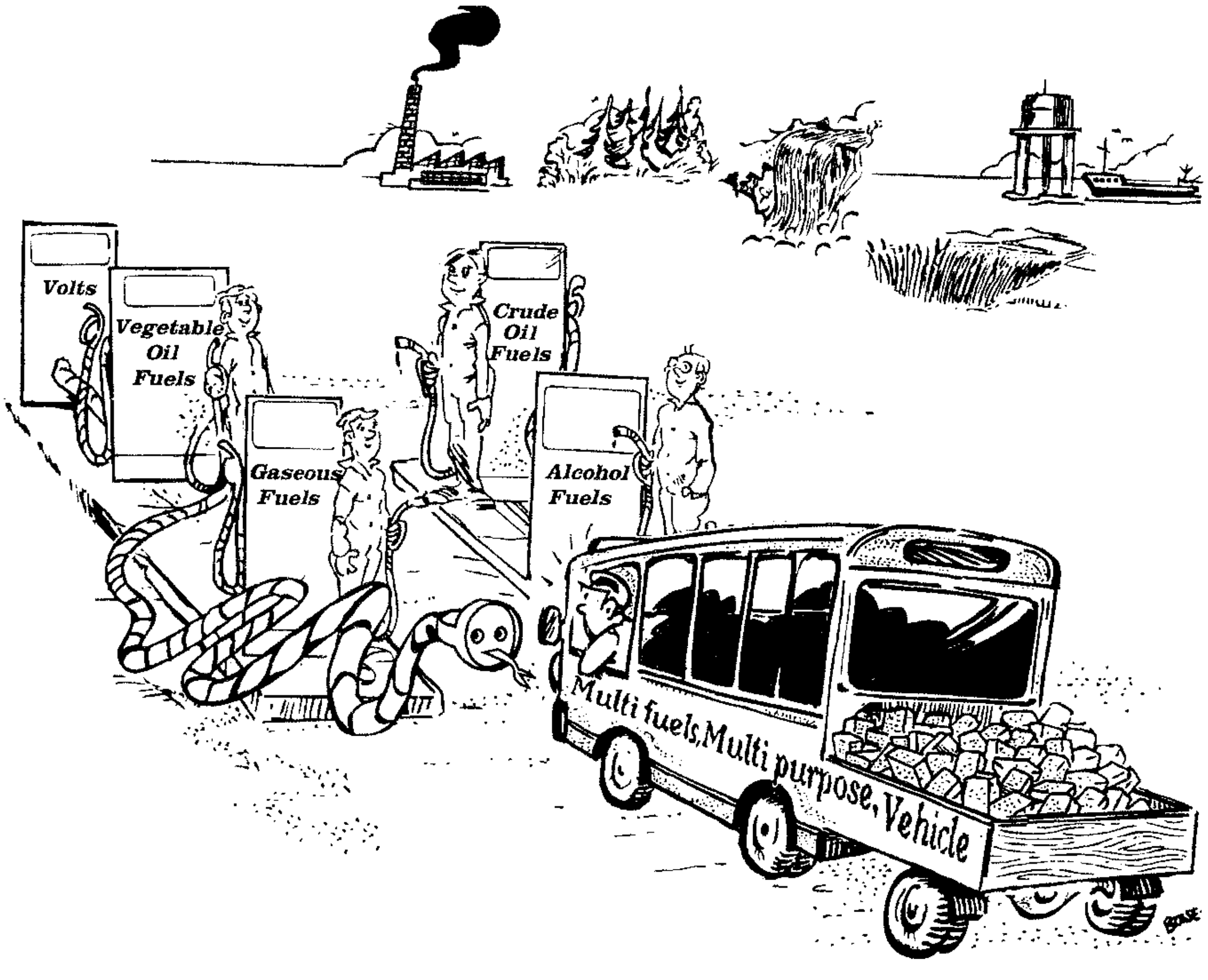
THE

LIFE OF FUELS

MOTOR FUELS FROM SOURCE TO END USE

An energy and emissions systems study of conventional and future options



FOREWORD

Which fuel is the best and why? This is a delicate question, which probably does not have one answer. It depends on the application and the national energy supply situation, etc. However, the question is often raised and the ambition of this report is to broaden the perspective on different motor fuels.

There is a need for comparing motor fuels from an energy efficiency standpoint as well as from an environmental. There also is a need for a systems approach and for comparing the whole fuel chains from source to end use.

Therefore, a project has been set up funded by companies and authorities representing different branches. A pre-study and state of the art report was accomplished during 1990, which defined the scope for this main project. A Steering Committee was set up including reperesentatives from all financiers. These have been given several opportunities to comment on the work. However, Ecotraffic is responsible for the contents of this report. The project has been funded by:

Federation of Swedish Farmers	represented by	Lars Dahlgren
OK Petroleum AB	"	Bengt Sävbark
Swedish Environmental Protection Agency	"	Eva Jernbäcker
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Swedish Transport Research Board	"	Christine Wallgren
Vattenfall AB	"	Hans Gransell (chairman)

Arne Johansson, Ecotraffic, has been project manager and has written the report together with Åke Brandberg and Anders Roth.

Bernt Gustafsson, ETU AB, has been contracted as independent scientist to review methods and calculations in the report.

We would like to express our appreciation for the supportive work, which has made this study possible.

Stockholm, March 1992.

Hans Gransell
Vattenfall AB
Chairman, Steering Committee

Mats Ekelund
Ecotraffic AB
Managing director

EXECUTIVE SUMMARY

BACKGROUND

Alternative motor fuels have been debated, investigated and to some extent used in many countries over the years. Promising RD&D results on exhaust emissions from alternative motor fuels operation have pushed the issue about supplementing conventional crude oil based motor fuels with one or more of the alternative fuels of either fossil or biomass origin. Alcohols, gaseous fuels, vegetable oil as well as electricity have been frequent in debate and in field tests. This debate has received extra attention in countries where security of supply is a concern.

Various airborne emissions have caused grave concern about climatic, environmental and health impacts. Discharges are currently at levels that require immediate actions to counter severe future problems.

Expected reductions of evaporative and exhaust emissions, reduced noise and decreased dependency on foreign crude oil products have been the rationale for the work with these fuels. Additionally, energy efficiency has been increased in engines using conventional fuels and the quality of these fuels has been improved. Further quality and efficiency improvements are expected from conventional as well as from alternative motor fuels.

SCOPE AND OBJECTIVES OF THE WORK

Comparing fuels from energy and environmental aspects is the objective of this study. Energy turnover and discharges of airborne emissions in the whole fuel chain, from source to end use, have been defined. Steps along the whole process have been calculated and compared, using published and given information as well as information on specific models, in the following areas.

- o Energy efficiency
- o Discharges of greenhouse gases
- o Discharges of acid gases

Moreover, certain discharges that are suspected or do affect health and environment have been qualitatively discussed.

Fuels that have been investigated are:

- o "Urban Diesel Oil" (about 0.001% weight sulfur).
- o Gasoline, (reformulated, leadfree, 95 octane, ≤ 0.01% weight sulfur)
- o Propane (field and refinery)
- o Natural Gas (mainly methane)
- o Biogas (methane)
- o Methanol (natural gas and biomass feedstock)
- o Ethanol (various biomass feedstock with fossil and bio process energy)
- o Rapeseed Oil Methyl Ester, RME (fossil and biomass process fuel)
- o Hydrogen (water feedstock, hydropower and natural gas powered process)
- o Electricity (Swedish average production and natural gas condensing plant)

Commercial and tentatively commercial size production is assumed. All infrastructure extraction, processing and distribution, is considered in existence before calculations.

RESULTS

Results from an urban bus and car operation, beginning with the fuels as raw material and following them through processing to end usage, are the following:

ENERGY EFFICIENCY relative to reference fuel (the higher figure, the better)

	Transport work per unit of fossil fuel input		**Transport work per unit of total energy turnover**		
Fuel	**CAR**	**BUS**	**CAR**	**BUS**	
Biogas(biogas process fuel)	No net fossil fuel need		0.7	0.6	
Electricity(Swedish average)	29	14	3.2	1.5	
Ethanol (tree residues, CASH)	17	14	0.5	0.5	
Methanol (tree residues)	12	10	0.6	0.5	
Hydrogen (hydro power)	8.3	-	0.4	-	
Methanol (energy forest)	7.5	6.3	0.6	0.5	
Ethanol (energy forest, logen)	6.1	5.2	0.4	0.4	
Ethanol (wheat, straw)	5.6	4.8	0.5	0.5	
Biogas (fossil process fuel)	4.4	3.5	0.8	0.6	
RME	-	3.4	-	0.8	
Ethanol (wheat, fossil fuel)	1.2	1.1	0.6	0.5	
Urban Diesel Oil	-	**1**	-	**1**	Reference fuel
Propane (refinary)	1.1	0.9	1.1	0.9	
Natural Gas	1.2	0.9	1.2	0.9	
Electricity (NG cond.plant)	1.8	0.9	1.8	0.9	
Gasoline	**1**	-	**1**	-	Reference fuel
Methanol (natural gas)	0.9	0.8	0.9	0.8	
Hydrogen (natural gas)	0.3	-	0.2	-	

AIRBORNE EMISSIONS relative to reference fuel (The lower figure, the better).

	Greenhouse gases (excl bio-CO2)		**Acid gases** (SOx and NOx)		
Fuel	**CAR**	**BUS**	**CAR**	**BUS**	
Electricity (Swedish average)	0.03	0.06	0.05	0.02	
Hydrogen (hydro power)	0.06	-	1	-	
Methanol (energy forest)	0.2	0.19	1.3	0.6	
Ethanol (tree residues, CASH)	-	0.22	-	0.7-0.9	
Ethanol (energy forest, logen)	-	0.31	-	0.8-1.1	
Biogas (luceme)	0.25	0.31	1.3	0.5	
RME	-	0.34	-	1-1.3	
Ethanol (weat, straw)	-	0.43	-	0.8-1.1	
Electricity (natural gas)	0.3	0.69	0.1	0.04	
Natural Gas	0.7	0.88	0.8	0.35	
Propane (refinery)	0.9	0.94	1.5	0.35	
Methanol (NG feedstock)	0.9	0.94	1.7	0.65	
Urban Diesel Oil	-	**1**	-	**0.9-1.1**	Reference fuel
Gasoline(lead free, 95 oct.)	**1**	-	**1**	-	Reference fuel

CONCLUSIONS

Results of this study can be utilised to compare energy resource demand and airborne emissions in various future motor fuels scenarios.

1. CHOICE OF FUELS FROM AN ENERGY SUPPLY POINT OF VIEW

Annual road transportation energy use in the OECD countries was about 30.000 PJ during the late 1980:s. Total road vehicle use, fully dominated by crude oil fuel products, accounts for some 49% of the total OECD use of oil . Future increasing needs for energy, in developed as well as in less developed countries, may become critical in many aspects. New sources of energy will therefore need to be extracted. In a short term perspective natural gas as a primary source of energy seem most adequate.

Biomass fuels offer a route to multiply fossil energy input to motor fuels several times. Energy turnover per unit motor fuel is, however, high due to the nature of the feedstock. The large energy differences in processing the fuels can be used in arguing for the continuation of using fossil fuels in the transport sector and bio feedstock in other less complicated processes. This would leave transports in an undesirable dependency of fossil fuels.

Local sources of energy may be considered for other than efficiency reasons. Employment, agricultural and security of supply are such reasons.

2 HEALTH AND ENVIRONMENTAL CHOICES

Energy supply or efficiency is seldom the primary criteria when considering benefits and drawbacks for a given fuel. More pressing issues, like environment, should take precedence and may lead to other choices. An example of greater value or higher priority can be when fossil fuels fail to meet stringent exhaust emissions requirements including the regulation of new compounds or discharges of greenhouse gases.

Choices that could be considered more important than energy efficiency are when

- to reduce greenhouse gases and oxidants substantially. -Non-fossil energy is preferable.
- to reduce acid gases. -The use of electricity and fuels/engine concepts with three way catalysts (TWC) are preferable.
- to reduce genotoxic emissions. -Electricity and chemically simple fuels, such as methane, methanol and ethanol are preferable, especially along with catalytic treatment.

NEEDED ACTIVITIES

Short and long term needs and obstacles should not conflict, they should rather support each other in as much as short term decisions should be a step towards the long term objectives. Long term decisions need to be made in order for the industry to adjust to new premises.

1 Systems and economics analyses

An alternative fuels breakthrough in the market place means that new or adapted distribution network and infrastructure needs to come into place. Staff need education about new products and tools, repairshops need to be adapted etc. A change requires investments and, therefore, the following economic consequences need to be studied:

1. Cost vs. environmental benefit (i.e. currency unit/unit reduced NOx, CO2 etc)
2. Cost vs. independency from foreign import
3. Cost vs. change in employment
4. Costs for individuals, companies, distributors, manufacturers and society
5. Step by step activities for changing
6. Potential fuel volume from available land area and competitiveness between fuels from biomass
7. Governmental, Industrial and Users ways of stimulating the introduction of desirable alternatives.

2 Bio-process RD&D

Non-fossil fuels are preferable for many reasons. Major RD&D activities should be directed towards reducing energy use when producing new fuels. Processing gases (methane and in the longer term possibly also hydrogen), alcohols (methanol and ethanol) and various vegetable oils from biomass will benefit from such RD&D activities.

3 Electric vehicle operation

Electric vehicles suffer from the high cost of low battery storage capacity. Hybrid vehicles may be a solution and should be considered the immediate step on the route towards a market of well developed hybrids and fully electrified vehicles, each for its niche. Major RD&D activities need to take place to meet the obstacles that electric vehicles are facing. Electric vehicles, considering the Swedish production mix of electric energy, are desirable from climatic, environmental and health aspects.

4. Immediate action (short term, leading towards long term goals)

Change to new, if necessary, fossil feedstock in the transport sector even if it does not reduce dependency in the short term. The use of alcohols and methane as an immediate step of training would be useful to increase knowledge and awareness. By accepting a step by step change over towards bio based fuels, security of supply can be increased in a longer perspective. Forceful RD&D will improve the production processes of bio-fuels to a more competitive level.

5 R&D on methodology

Methods of calculating and comparing in this study have been investigated and approved by an independent scientist. Methods of comparison still need to be an item for development as framework and details on individual steps need further definition.

<u>MOTOR FUELS FROM SOURCE TO END USE</u>
Final report on an energy and emissions system study

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MOTOR FUELS FROM SOURCE TO END USE

Final report on an energy and emissions system study from
ECOTRAFFIC AB, Stockholm, Sweden

Abstract

This paper reports the findings of a study on some conventional and alternative motor fuels for road vehicles which is prepared by the consulting company Ecotraffic AB on behalf of a group of clients including some government agencies, a motor fuels producer, a utility company, and some interest group foundations.

The purpose of this study is to explore energy utilization, emissions and environmental impact, touching somewhat on health aspects, relative to the full energy chain for automotive fuels, from the primary energy source up to and including the end use in road vehicles.

The scope of the study comprises also to clarify methodology used for energy and emission accounts, and to elaborate the way of presenting the fairly complex results.

The fuels dealt with are diesel oil (low sulphur standard and urban), gasoline (standard lead free and reformulated), propane (LPG), methane in the form of natural gas and biogas (lucerne) respectively, methanol from natural gas and from biomass (energy forest and tree residues), ethanol from biomass (wheat, energy forest and tree residues), vegetable oil methyl ester from rapeseed (RME), hydrogen (electrolysis of water), and electricity (Swedish average generation and natural gas based).

The entire fuel chains are basically split up in a few steps nominally called extraction, transport, conversion, and distribution. The details of these steps differ between the motor fuels. For some steps, especially for the biobased motor fuels, alternatives for the process fuels involved are studied.

The end use implications of the fuels are related to the use of them in well defined engines/motors operating in well defined vehicles. This means that well documented laboratory values for established engines/motors in existing vehicles in most cases are relied upon for the end use energy and emissions. Three model vehicles are used to illustrate the impact at the use of the fuels studied. These are a passenger car (curb weight 1,2 ton; petrol fueled for reference), a medium heavy distribution truck (c.w. 5 ton; diesel oil fueled for reference) and an urban bus (c.w. 11 ton; diesel oil fueled for reference).

The results are presented in tables and diagrams for each case. For the individual fuel chain this information is quite comprehensive. In order to facilitate comparison of fuels and also to give an idea of how to interpret the impacts on total energy balance and on the emission situation, the fuels are presented together in broad measures with respect to energy resource use (fossil and renewable), greenhouse gas emissions (CO_2-equivalents), and acid gases (NO_2-equivalents) respectively.

The figures used in most of the presentations are related to the energy content in the motor fuels. This means that, for instance, the energy diagrams present figures being MJ/MJ_{fuel} expressed as percent of motor fuel energy and the emissions diagrams present figures in mg or g per MJ_{fuel}.

From the comparison of the fuels studied, we note that the energy turnover is much higher (up to about triple) in the biomass based system than in the fossil diesel oil system. This is because of the higher energy input to produce and convert the biomass. The energy share for end use as motor fuel is somewhat less than half of the energy turnover in the bio-methanol and the ethanol chains compared to almost 85-90 % for the fossil oil based chains.

The consumption of fossil resources is, however, considerably lower for the biomass based fuels, provided that biomass is used as process fuel. In theory, the bio-chains may consume almost no net fossil resources at all, if fertilizers also are produced from biomass feedstock or credit for by-product fertilizers can be obtained.

In order to compare the energy resource utilization at actual transport work done, the specific fuel consumption per vehicle kilometer for the relevant fuels are compared in a bar chart for each of the three model vehicles.

The contribution to the emission of greenhouse gases is for the bio-fuel chains less than half of these emissions from the fossil oil based fuel chains. The greenhouse effect may in fact be still somewhat lower for the biomass chains, since energy crop cultivations, particularly energy forests, will serve as a carbon dioxide sink by increased accumulation of carbon in root systems and in the soil. This is, however, not accounted for in the data presented since they only comprise the biomass harvested.

Acidification potential is highly dominated by the emissions of nitrogen oxides and at the emissions at the end use. Diesel oil and vegetable oil show the highest figures, and the lowest figures are obtained with fuel/engine-combinations which can use catalytic NOx-reduction. The bio-chains give rather high contributions to NOx-emissions at the biomass production and conversion stages.

The impact of the emissions from the diverse motor fuels will, of course, depend on the road share of the transport sector, on the penetration of new fuels on the market and on the share of man-made emissions in relation to natural emissions. Some short discussions on these themes are presented and the three geographical levels (local, regional, and global) are considered.

Resources and costs are discussed in broad terms relating to primary energy resources, world market prices and cost of vehicle fuels.

The conclusions of the study are summarized as follows:

1. Methodology seems adequate and useful.

2. Emissions sufficiently quantifiable except for oxidant and

health affecting ones, which presently can only be qualitatively assessed because of lack of data for all fuels studied.

3. Impacts on health, environment and climate require model calculations, which are beyond the the scope of this study; emissions data serve as input.

4. Energy resource use is adequately covered, concluding
   * energy turnover depends on type of feedstock; 20-300 % higher in renewable systems compared to fossil ones
   * fuels for end use 17-70 % of resource input in renewable systems compared to 85-90 % for fossil only ones
   * fossil energy inputs in renewable systems can be only a fraction of that in fossil only ones and may be negative, i.e. the system saves fossil energy elsewhere.

5. Greenhouse-enhancing emissions in the whole fuel chain are somewhat lower for alternative, fossil-based motor fuels (propane, natural gas, methanol) and considerably lower (60-95 %) for renewable systems (hydropower particularly and photosynthesized biomass); emissions are expressed as CO_2-equivalents converted by use of IPCC factors, which are not yet finally established.

6. Acid gas emissions are combined to common number based on acidifying power but synergistic effects are not included; emissions are dominated by nitrogen oxides at end use; renewable systems have greater share of acid gas emissions during production; fuel/engine combinations, which allow use of three-way catalytic reduction of nitrogen oxides, show lowest NOx-emission level; alcohols give lower NOx-emissions than diesel oil in diesel engines.

7. Oxidant-forming organic emissions for local conditions (considerably) lower for most alternative fuels due to less reactive fuel components and lower emissions of reactive organic compounds; ranking methane, methanol, propane/ethanol.

8. Genotoxic, cancer initiating/promoting, emittants (gaseous alkenes, benzene, aldehydes, NOx (?), particle-bound and semivolatile PAC:s) are lowest for electricity, methane and methanol fuel/engine systems and highest with diesel oil and gasoline.

9. The results of this study could be utilized to compare energy resource demand and airborne emissions at various transport scenarios for possible near-future vehicles.

Finally, based on the result of the study, some comments are presented on the themes:

* choice of motor fuels in an energy supply view
* needs other than energy supply
* environmental choice among rated fuels
* economics for a change of systems and techniques
* possible short term actions.

DRIVMEDEL FRÅN KÄLLA TILL ANVÄNDNING
Slutrapport för en energi- och emissionssystemstudie
från ECOTRAFFIC AB, Stockholm

Sammanfattning

I denna rapport redovisas resultat av en studie avseende konventionella och alternativa drivmedel för vägfordon. Studien utförs vid konsultföretaget Ecotraffic AB på uppdrag av en grupp intressenter, däribland några statliga myndigheter, en drivmedelstillverkare, ett kraftproducerande företag och några intresseorganisationer.

Syftet med studien är att undersöka energianvändning, luftburna emissioner och miljöpåverkan, till viss del även hälsoaspekter, som är förenade med den fullständiga energikedjan för vägfordonsdrivmedel, nämligen från primärenergikällan till och med slutanvändning i motorfordonet.

Syftet med studien omfattar även klarläggande av metoder för energi- och emissionsredovisning samt att utarbeta ett praktiskt sätt att presentera de tämligen komplexa resultaten från sådana redovisningar.

De drivmedel som ingår i studien är dieselolja (standard lågsvavlig samt tätorts-), bensin (standard blyfri samt reformulerad), propan (LPG), metan i form av naturgas och biogas (från luzern), metanol från naturgas och från biomassa (energiskog samt trädrester), etanol från biomassa (vete, energiskog samt trädrester), vegetabiloljeester (från raps, RME), vätgas (elektrolys av vatten) och elektricitet (svensk nationell elproduktion samt naturgasbaserad).

Drivmedelskedjan behandlas uppdelad i några huvudsteg, nominellt kallade utvinning, transport, konvertering och distribution. För några steg, särskilt för de biomassebaserade drivmedlen, studeras några alternativ för processbränslet.

Slutanvändningen av drivmedlen relateras till användningen av dem i väldefinierade motorer, som arbetar i väldefinierade vägfordon. Detta innebär att väl dokumenterade laboratorievärden för etablerade motorer i befintliga fordon används för att uppskatta inverkan av slutanvändningens effekter på energianvändning och emissioner. Tre modellfordon används för att illustrera drivmedelsanvändningen. Dessa är en personbil (tjänstevikt exkl förare 1,2 ton; bensindriven som referens), en medeltung distributionslastbil (tjänstevikt exkl förare 5 ton; dieseloljedriven som referens) samt en tätortsbuss (tjänstevikt exkl förare 11 ton; dieseloljedriven som referens).

Resultaten presenteras i tabeller och stapeldiagram för varje fall. För de individuella drivmedelskedjorna är denna information tämligen omfattande. För att underlätta jämförelse mellan drivmedel och även för att indikera tolkningsmöjligheter för totala energibalanser och miljöpåverkan presenteras drivmedlen tillsammans med avseende på energiresursanvändning (fossil och förnybar), växthusgasutsläpp (CO_2-ekvivalenter) respektive försurande utsläpp (NOx-ekvivalenter).

De siffror som används i alla presentationer är relaterade till energiinnehållet i drivmedlen. Detta innebär att t ex energidiagrammen använder siffror som är mätetal i MJ/$MJ_{drivmedel}$, uttryckta som procent och emissionsdiagrammens siffror är mätetal uttryckta i mg eller g per $MJ_{drivmedel}$.

Från jämförelsen av de drivmedel som studerats, noterar vi att energiomsättningen är mycket högre (upp emot den dubbla) i det biomassebaserade systemet än i det fossilbaserade dieseloljesystemet. Detta beror på den högre energiinsatsen för att producera och konvertera biomassan. Energiomsättningen vid användning som motordrivmedel är något mindre än halva totala energiomsättningen i biometanol- och etanolkedjorna, medan motsvarande andel är nästan 85-90 % för de fossiloljebaserade kedjorna.

Förbrukningen av fossila resurser är emellertid avsevärt lägre för de biomassebaserade kedjorna, förutsatt att biomassa används för att generera processenergin. Rent teoretiskt kan bio-kedjorna klara sig nästan helt utan fossila resurser, om konstgödningen också framställs från biomassa eller kreditering av biprodukter kan rättfärdigas.

För att få en uppfattning om energiutnyttjandet vid verkligt transportarbete jämförs den specifika drivmedelsförbrukningen per fordonskilometer för de relevanta bränslena i ett stapeldiagram för vart och ett av de tre modellfordonen.

Bidraget till emissionerna av växthusgaser är från bio-kedjorna mindre än hälften av det från fossilolje-kedjorna. Växthuseffekten kan möjligen hävdas vara ännu lägre för bio-kejorna, eftersom energiväxtodlingar, i synnerhet energiskogar, utgör sänkor för koldioxid genom den ökade bindningen av kol i rotsystem och i jorden. Detta framgår emellertid inte av de presenterade siffrorna, eftersom de endast innefattar skördad biomassa.

Försurningspotentialen domineras starkt av kväveoxidemissioner, som uppstår vid användningen i förbränningsmotorer. Dieselolja och växtolja visar de högsta siffrorna, medan lägst siffror erhålls vid drivmedel/motor-kombinationer, som kan använda katalytisk NOx-reduktion. Bio-kedjorna ger ganska höga bidrag till NOx-utsläpp vid produktions- och konverteringsstegen.

Effekterna av emissionerna från de skilda drivmedlen beror naturligtvis på vägtransporternas andel av transportsektorn, på nya drivmedels marknadsandelar och på relationen mellan naturliga och från människans aktiviteter härrörande emissioner. Några korta diskussioner på dessa temata genomförs och de tre geografiska nivåerna - lokala, regionala och globala effekter - berörs.

Resurser och kostnader diskuteras i allmänna termer relaterade till primärenergiresurser, världsmarknadspriser och kostnader för drivmedel.

Studiens slutsatser summeras som följer:

1. Metodiken tycks adekvat och användbar.

2. Emissionerna är tillräckligt kvantifierbara utom för oxidanter och hälsopåverkande emissioner, vilka för närvarande endast kan kvalitativt värderas på grund av

bristande data för alla studerade drivmedel.

3. Effekter på hälsa, miljö och klimat kräver modellberäkningar, vilket ligger utanför ramen för denna studie; emissionsdata från studien är lämpliga ingångsdata.

4. Energiresursanvändningen är tillräckligt behandlad och leder till slutsatserna
   * energiomsättningen beror på typ av råvara; 20-300 % högre i förnybara system än i fossila
   * drivmedel vid slutanvändning är 17-70 % av resursinsatsen i förnybara system jämfört med 85-90 % i rent fossila system
   * insatsen av fossilenergi i förnybara system kan uppgå till endast en bråkdel av den i helt fossila system och kan vara negativ, d v s systemet sparar fossil energi någon annan stans.

5. Emissioner som ger växthuseffekt är över hela kedjan något lägre för alternativa fossila motordrivmedel (propan, naturgas, metanol) och avsevärt lägre (60-95 %) för förnybara system (särskilt vattenkraft och fotosyntetiserad biomassa); emissionerna uttrycks i CO_2-ekvivalenter med hjälp av IPCCs faktorer, som dock ännu inte är slutligt fastlagda.

6. Emissioner av försurande gaser kombineras till en kvantitet på basis av rent kemisk försurningskraft utan att eventuella synergistiska effekter beaktas; emissionerna domineras av kväveoxider från slutanvändning; förnybara system har större andel försurande emissioner under framställning; drivmedel/motor-kombinationer som tillåter användning av trevägskatalytisk reduktion av kväveoxider visar lägst NOx-emissionsnivåer; alkoholer ger lägre NOx-emissioner än dieselolja i dieselmotorer.

7. Oxidant-bildande organiska emissioner är på det lokala planet (avsevärt) lägre för de flesta alternativa drivmedel på grund av mindre reaktiva beståndsdelar i drivmedlen och lägre emissioner av reaktiva organiska föreningar; rankningen är metan, metanol, propan/etanol.

8. Genotoxiska cancerframkallande/-befrämjande emissioner (gasformiga alkener, bensen, aldehyder, NOx(?), partikelbundna och halvflyktiga PAC) är lägst för drivmedel/motorsystem för elektricitet, metan samt metanol och högst för dieselolja och bensin.

9. Resultaten av studien kan användas för att jämföra energiresursbehov och luftburna emissioner vid olika transportscenarier för nära framtida fordon.

Slutligen presenteras med anledning av studiens resultat några kommentarer under rubrikerna:

* val av drivmedel från energiförsörjningssynpunkt
* andra behov än energiförsörjning
* val mellan drivmedel från miljösynpunkt
* ekonomiaspekter på val av system och teknik
* möjliga åtgärder på kort sikt.

MOTOR FUELS FROM SOURCE TO END USE
Final report on an energy and emissions system study

1. INTRODUCTION

1.1 Background

Traditionally, transport and motor fuels have only been evaluated for energy, emissions and environmental impact when used (i.e. in motor vehicles). However, energy is required and fuels truly begin to have an impact on the environment long before this - in the case of fossil fuels, from the crude oil extraction process. After the basic recovery of primary energy, fuels must be refined, stored and distributed. Each of these processes in turn involves additional energy use and environmentally adverse effects.

In order to make more accurate comparisons of motor fuel energy efficiency and emissions, all related energy usage and emissions should be accounted for. Hence, the need to modify or replace the traditional "end-use" view with an enlarged system philosophy.

The boundaries of the system are also relevant when energy utilization of the various fuels and effects of the various emissions are discussed. To give an example, the energy use for an electric household appliance differs in measured value across the supply system. The lowest reading is at the domestic electricity meter. A higher value is associated with the corresponding input from the power plant to the distribution grid and a still larger energy quantity is associated with the primary energy input to the power plant. Similarly, some emissions have a major impact on the local environment (health problems), others on the regional environment (e g acidity), while still other emissions have resulting effects at the global level (e g greenhouse gases). Thus, there is a demand to make clear where the emissions affect the environment, and which effect originates from which subprocess along the fuel chains.

The effects on health, the environment and the climate, due to vehicle emissions, are complex. To give an example, a certain value of the total emission figure for hydrocarbons, which is quite often referred to as an environmental measure, may have very different effects on health and environment according to the fuel it originates from. Obviously, making proper comparisons of fuel emissions requires a thorough understanding of their fine structure.

When dealing with these problems to achieve useful results, it is especially important that decisions and actions be grounded in a sufficiently broad systems analysis. The desire to bring all of the above into focus, shared by a number of interested parties, provides the incentive for this study.

Preceding this project is a pre-study, published /63/ at the beginning of 1991 in a report series from the Swedish State Power Board. (The Swedish State Power Board is one of the pre-study sponsors.)

1.2 Study objective

The purpose of this study is to examine a number of road vehicle fuels for (1) environmental consequences due to atmospheric emissions, and (2) the energy efficiency associated with these fuels. Consideration will be given to the entire handling process beginning with the basic source. Emphasis will be placed on the analysis of the generally neglected portions of the handling process antecedent to a fuels's use in vehicles.

A thorough treatment will be made for diesel fuel (typical European; reference fuel for heavy vehicles), reformulated diesel fuel (urban diesel oil), gasoline (lead free Eurograde; reference fuel for light vehicles), reformulated gasoline, propane (LPG), methane (natural gas and biogas), methanol, ethanol and electricity. Furthermore, vegetable oils and hydrogen will be comprehensively dealt with.

Additionally, an appropriate presentational format will be devised to illustrate environmental consequences or "load", and energy utilization. This will facilitate the treatment of information from relevant literature and in-coming data from the fuels handling analysis.

In summary, the study's main objectives are two-fold:

1. Create a synthesis of the best available data on the fuels being analysed.
2. Devise a presentational format illustrating
   a. environmental load due to air-borne emissions from motor fuels, including some health aspects
   b. a reasonably complete energy balance for these same fuels.

1.3 Study approach

From our experience of the field of conventional as well as alternative road vehicles' fuels, supplemented with a thorough check of current literature on the topic of extended energy and environment studies to the full energy chain, we will suggest a method to deal with the general road vehicle fuel in a practical way in order to get a fair comparison of most of the possible energy, environment and health aspects on the full fuel chains.

We will also rely on the special knowledge of some fuels or vehicle techniques with the sponsors of the study, and we will furthermore try to get further evidence on questionable data from organisations operating in the various fields touched upon.

With regard to biobased fuel chains we restrict the investigation to absolute values of energy inputs and airborne emissions experienced or expected. It has not been possible to include, for instance comparisons to other land use alternatives or the very interesting question on the total emissions (including also waterborne) of traditional land use.

There are, of course, uncertainties in the figures used by us, more than what actually have been indicated explicitly in some sections of the report. A general sensitivity analysis would be of interest to undertake on the basis of the figures of the report. This, however, was not intended from the beginning and would benefit very much from a computer based spread-sheet handling of all data. If the methodology used in our study is found to be useful for its purpose of comparison of the alternatives, it could be well worth to try to computerize our procedure.

Regarding airborne emissions, especially the generally toxic ones (health affecting), it has to be kept in mind that the interest for these are fairly recent. This means that techniques for measurements and analyses are not fully developed yet, there is no general agreement on which components to focus on, etc. Thus, figures for the more technically mature engine/vehicle concepts are not necessarily considerably better founded than those for more spectacular concepts.

Being aware of the many difficulties when actually trying to put comparable figures on certain features concerning energy and environment in general, we try to excuse our shortcomings in advance by adopting as our motto for this study the saying, which is often attributed to Myron Tribus of Exergy Inc, USA:

"It is much more important to be able to survey the set of possible systems approximately than to examine the wrong system exactly. It is better to be approximately right than precisely wrong."

1.4 Layout of the report

We try to explain the philosophy of the study and advocate the methods used and stands taken. The concepts used by us are not necessarily very conventional and thus we define them and justify them wherever we feel a need for it.

In chapter 2 of the study the general assumptions and the methods utilized are explained. The fuels and their full fuel chains are defined, the basic philosophy of our dealing with energies and emissions is described and justifications are presented where we feel a need for them. In chapter 3 and 4, on energy and emissions respectively, the various fuels are discussed, fuel by fuel, and the results from each fuel chain are presented fuel-wise in a lucid way, where possible in the form of bar charts.

The treatment of the fuel (or energy) chains, being generally split into a number of subprocesses, is presented in two major steps. The first step covers the process from primary energy to the ready-made fuel in the tank, which is also the main subject of the study. The energy inputs and the corresponding emissions are compared for each fuel at this stage of the study. The second step involves the conversion of fuel energy to transport work via an engine/motor and the vehicle drive line. In order to enable the reader to get an idea of the consequences to energy balance and environment of the utilization of the fuels to get transport work done, we give typical energy consumption values and emission values for three typical vehicles (a car, an urban bus and a medium heavy distribution vehicle) at the appropriate driving schemes for each fuel and compare them with the reference values for each vehicle type.

The fuels studied are compared energy- and emission-wise in chapter 5. At the energy comparisons, fossil and total, within the boundaries of the systems more or less clearly defined, energy use are considered. At the emissions comparisons, an attempt is made to collect the various emissions considered in three major groups, namely greenhouse gases, acid gases and air toxics.

Also in this study, there is a brief discussion of resources demanded and the typical costs of these in a separate chapter (number 6). Finally, in chapter 7 some general conclusions are drawn, when needed based on particular conditions in Sweden, and some recommendations are given on possible actions to improve flexibility in primary energy supply to the transport sector in Sweden and/or the environment.

2. GENERAL ASSUMPTIONS AND STUDY METHODS

This study is primarily a study of energy use, emissions to the atmosphere and environmental effects related to the full fuel chain for a number of vehicle fuels. Thus, we will not treat very much questions on safety aspects or costs for the fuels. Nor will we study possible accidents, e g in the exploitation or the distribution steps, and their environmental impacts and the costs of them. There will, however, be a short discussion on costs in a chapter on resources and costs.

At the analysis of the full energy chains of the fuels (extraction/production, transport, storage) we have put stress on mapping out and studying those alternatives for the fuels which give the highest energy efficiency and the lowest environmental load.

For all energy chains we have assumed that all infrastructure and equipment needed for the activities are there. No energy use or environmental impact from the production, transportation and erection of such items have been considered. A consequence of this limitation could be that fuels with very complex and resource demanding installations in the energy chain are favoured at comparison with other fuels with smaller system demands.

2.1 Energies

In this study we split the full energy chain for the motor fuel generally into six main links/subprocesses, namely:

1. primary energy exploitation/extraction
2. primary energy transport
3. conversion to fuel
4. fuel distribution
5. conversion in vehicle engine
6. personnel and goods transport/conversion to transport work

Any of these are, when deemed practical, further divided into subprocesses of its own.

The central theme of this study is the motor fuel and thus we choose to focus on the motor fuel into the tank of the vehicle, which means the fuel at the end of subprocess 4 above. These four subprocesses will be the main topic of this section. The subprocesses 5 and 6 will be discussed in section 2.4 below.

For all the fuels (or rather fuel chains) we will give the energy inputs required to get a unit of motor fuel energy in the tank of the vehicle. The difference between the energy input in the subprocesses up to and including the fuel distribution and the energy output in the form of chemical energy bound in the fuel (its energy content) defines the energy balance of the fuel ready to use.

In the subprocesses, energy inputs are made from various sources. Depending upon the scale of the activities process, more or less energy is put in from external sources. For example, in a large scale petroleum refinery, process energy of all kinds is tapped from the main stream of primary energy (crude oil). In a minor refinery it may be that e g process electricity is bought externally while process steam is generated internally from the main stream products. Also at the extraction and transportation subprocesses for petroleum products the energy input could easily be considered as coming from the main stream.

Energy flows and concepts of possible use for the description of energy efficiency in various steps and parts of the full chain are discussed in appendix 2:1. The seemingly clear concepts defined in that appendix are a bit obscured by the conditions of real processes. Various products could be processed in the main stream. Some of these products could have conventional energy character, others could be by-products of some other character, e g animal feed. The way we intend to deal with these features is discussed in section 2.3 below. Our real handling of those matters will be explained in the separate fuel sections of the energy chapter (chapter 3).

2.1.1 Energy measures and units

At some stage in this study we shall have to measure for energy quantities. In thermodynamics the same energy measure is used for every energy form. The energy unit in the international unit system (SI) is the joule (J), which is equivalent to the watt-second (Ws) and also to the newton-meter (Nm).

It is established in many contexts to use the megajoule (MJ) as the energy content unit for fuels. In everyday life it has become practical to use the kilowatt-hour (kWh), which is related to the power unit, the kilowatt (kW), a convenient unit for ordinary household equipment, and the hour (h), a convenient time unit in everyday life. The conversion rate between those two units is 3,6 MJ per kWh. We shall try to use MJ for the energy unit throughout this study. This means that energy balances will be expressed in MJ and specific energy balances in MJ/MJ_{fuel}.

2.1.2 Electricity

Electricity, as the energy input to a process, has a special character. Even as a form of energy in comparison to kinetic (motive) energy, heat energy, chemically bound energy etc, electricity is different. In order to express the technical (thermodynamic) quality or usefulness of various energy forms, the concept of exergy is sometimes used. Electricity has a high exergy, i e it is technically very useful for executing work. However, in order not to complicate the conceptual frame of this study we try to avoid making explicit use of the exergy concept.

The traditional measure of the amount of electric energy in everyday life is the kWh. However, the number of electric energy units used in a process does not tell how much primary energy has been utilized to generate this amount of electric energy. That depends upon the method used for electricity generation. One (1) kWh of electricity from hydropower generation is equivalent to about 1 kWh of primary energy (1,05 with a turbine efficiency of 95%) in the form of potential energy for water. Another kWh generated in an oil fired thermal power plant of conventional type, is equivalent to about 3 kWh of primary energy in the form of chemically bound energy in the fuel oil. The same amount of energy used can thus be accounted for with numbers differing by a factor of three and still both numbers are correct. It is obvious that the number of electric energy units alone, in this context, conveys incomplete information.

In this study we consider electricity, when used as external input to the process or when treated as a motor fuel, as having two origins which are separately presented. One origin is the national power generation set-up in Sweden. The actual use of this system varies between the years. We define this system as having 50% of the power generated from hydropower, 45% from nuclear power and 5% from fossil fuelled thermal power (straight condensing mode). This is normally a slight overestimation of the fossil fueled power. According to the Swedish State Power Board, 48.6% of the power production for 1988 came from hydropower, 46.9% from nuclear power and 4.5% from fossil fueled power.

The efficiency of the fossil fueled power stations can be taken as 38% on the average. This means that each kWh of electricity from this origin is related to 1/0.38 = 2.63 kWh of fossil fuel energy. The average kWh from the Swedish power generation system is then equivalent to 5% of 2.63 = 0.13 kWh of fossil fuel energy. This is at the power station. The distribution losses from the fossil fueled power stations are assumed to be 5%, which means that each average Swedish kWh of electricity tapped from the grid, is equivalent to 0.14 kWh (0.50 MJ) of fossil fuel energy. (This is a very low figure of fossil fuel based electricity share in the national power supply. Similar low figures are found in Norway, Switzerland and France, but the typical European Community kWh of electricity is equivalent to 2.65 kWh (9.5 MJ) of fossil fuel energy.)

The other electricity origin considered is a natural gas fired, combined cycle power station of modern design, which gives an efficiency of 50% in the straight condensing mode. The generation of 1 kWh of electricity at such a plant is equivalent to 2 kWh of fossil energy (natural gas). It is assumed, as in the previous paragraph, that the distribution loss in the grid served by this power station is 5%. This implies that each kWh of electricity utilized somewhere in the grid supplied from this source is equivalent to 2.11 kWh (7.58 MJ) of fossil fuel energy in the form of natural gas.

The figures cited above will be used for external electricity used anywhere in the subprocesses studied in any chain, as well as in the section of this study where electricity is considered a vehicle fuel. It has, however to be recalled, that in many large scale subprocesses, electricity will be internally generated and hence some of the main stream primary energy will be considered for this purpose in the energy balance.

2.1.3 System boundaries

The quantity of energy utilized in any process depends very much on where the boundaries of the system are set. In a study like this, energy is one major topic and primary energies originate from sources of different types and at not fully compatible levels. Fossil fuel may be almost ready to use, e g natural gas, while biofuel raw materials have to be converted. Comparisons of figures have to be made with a good understanding of the system boundaries chosen. For practical reasons, we shall not be able to set the same boundaries for all motor fuel systems in this study. However, we shall try to point to the effects of the system boundaries when comparing motor fuels.

The handling of substitution crediting in some cases and the partitioning of energy inputs in some cases are also related to the system boundaries chosen. Furthermore, in biomass based systems, it is natural to include the cultivation energy (at a sustainable production level) among the inputs but not the solar energy coming into the cultivated area as an energy input. We shall not in every case actually define the system boundaries, but they are chosen in order to provide a practical treatment and they should be understood from the write-up for each case.

2.2 Emissions

The emissions basically of interest to this study are the emissions to the atmosphere generated by the use of conventional road vehicles. The best known of these emissions are those which are regulated by vehicle emissions laws. The still unregulated emissions from conventionally fueled vehicles are, however, not unimportant. Some of them cause genetic mutations in some organic cells under special circumstances, and they are believed to be able to do so even in human cells.

Furthermore, the introduction of alternative vehicle fuels will give rise to new types of emissions (or at least a considerable increase of minor conventional emissions) which are not yet regulated. This will probably give rise to discussions on the need for further regulation of vehicle emissions.

Also, the so called greenhouse effect has focused attention on what are called greenhouse gases, of which carbon dioxide (CO_2) is the most common, except for water vapour. Those gases have a considerable effect on the transmission of electromagnetic radiation in the far infrared (long wavelength) heat radiation through the atmosphere. It is expected that the increase of the greenhouse gases in the atmosphere will reduce the heat loss from the earth to the surrounding space, and that the temperature on this planet will consequently rise. According to many scientists, this temperature increase may be expected, in turn, to flood large lowlying areas because of the melting of part of the polar land ice and maybe also from the thermal expansion of the water volume of the oceans, when its temperature is eventually raised.

The following sections will give a basic description of the three groups of emissions mentioned, of the regulation levels discussed (if any) and of the methods to measure the emissions. Also the effects of the emissions will be indicated below but more thoroughly treated in later chapters. The major types of effects from atmospheric emissions are acidification, overfertilization, forming of oxidants, greenhouse effect, and health hazards.

One of the major reasons for this study is that the above mentioned emissions, when it comes to vehicle fuels, are normally considered only when released through the use of the vehicle. This has been the major event for atmospheric emissions in connection with vehicle fuels and still is. It may however change radically when alternative fuels are used. Electric vehicles, for instance, are commonly assumed to produce "zero emissions". Disregarding temporarily this extreme case, the handling of the vehicle fuels and the "raw materials" and the intermediate states for them give rise to emissions which should not be omitted in the comparison of alternative fuels.

Emissions from motor vehicles are quantified in various ways, depending on vehicle type. For light vehicles (cars) the emissions are normally expressed in grams per kilometer, g/km (or grams per mile, gpm). For heavy vehicles the quantities of emissions are commonly related to the mechanical energy output from the engine shaft. By convention the energy unit kWh is used for this mechanical work and the heavy vehicle emissions are thus normally recorded in grams per kilowatt-hour of mechanical work at the engine shaft, g/kWh. In the US Federal Test Procedure (FTP), emissions are recorded in g per bhph (brake horsepower hour).

Of course, the emissions vary with how the engine works and whether it is a light or a heavy vehicle. The operation of the engine has thus to be known in order to enable evaluation of any emission figure stated. We shall revert to these practical problems in later chapters on vehicle use. Also, they will be mentioned in the following sections on the emission types considered.

2.2.1 Regulated emissions

Regulated <u>emissions from vehicles</u> are some groups of components which have long been considered detrimental to the environment (atmosphere) and organic life (especially human). The regulations vary between countries and between vehicle types.

In Sweden some components of the exhaust gases from cars (light vehicles) have been regulated by law for several years. Those components are nitrogen oxides ($NOx = NO + NO_2$, but not including N_2O), (unburned) hydrocarbons (HC) and carbon monoxide (CO). HC will in the future refer to non-methane organic gases, with adjustment for different atmospheric reactivity to reflect the large variations in this respect and lower reactivity for most of the alternative fuels and the compounds originating from them in the exhaust gas. The regulations are formulated as a maximum amount of the component emitted per vehicle kilometer, when operated in a specified manner (transient cycle on a chassis dynamometer). Examples of present regulations in Sweden and California are presented below:

Table 2.1 **Present Swedish and Californian maximum allowed emissions from cars; also from future (transitional) low emission vehicles, (T)LEV; all values in g/km; durability 80 000 km**

	Sweden	California	TLEV*	LEV**
CO (carbon monoxide)	2.1	4.3	2.1	2.1
HC (hydrocarbons)	0.25	0.25	0.078	0.047
NOx (nitrogen oxides)	0.62	0.25	0.25	0.124
HCHO (formaldehyde)	-	-	0.009	0.009
C_6H_6 (benzene)	-	-	-	0.002

* introduction 1994

** introduction 1997

Furthermore, there have been for some time and still are some restrictions on the particle content of the exhaust gases, which has been quantified by a paper filter soiling test. This has been relevant only for diesel oil fueled vehicles, cars and heavy duty vehicles.

For the time being there are laws approved in Sweden, but not in operation until the 1993 models, regulating the emissions from heavy (duty) vehicle engines, except for soot. Limitations regarding four types of emissions from heavy vehicle engines will be introduced in 1993. The specified maximum outlets are presented in Table 2.2 below. The values will be measured according to the European method ECE R49, using an engine dynamometer. Also in Table 2.2, the EC limit values suggested to be valid from 1996 are presented. It is decided in Sweden to try to introduce in advance, with the help of economic incentives, vehicles which can cope with the coming EC limit values with respect to noise and exhaust pipe gases including an endurance requirement.

Table 2.2 **Some maximum allowed emissions from heavy vehicle engines; all values in g/kWh engine work (brake kWh)**

	Sw.1993	EC1996[1/]
NOx (nitrogen oxides)	9	7
HC (hydrocarbons)	1.2	1.1
CO (carbon monoxide)	4.9	4.0
particles	0.4	0.15

[1/] Environmental category 1 and 2 from 1993 in Sweden (with economic incentives)

It should be noted that of the emissions in Table 2.2, only CO is chemically well specified and its effects on the environment and the whole biosphere could be studied. The other emission types are not very well defined from a chemical point of view and can comprise chemical compounds of quite varying effect on the environment and the biosphere.

The above suggested limitation values are related to conventionally fueled vehicles. When considering alternative fuels, the same numbers will probably be required. They will, however, probably be calculated by specific formulas applied to the values from the specified measurement procedures for each specific fuel.

Also emissions from power stations are regulated in most countries. In Sweden, the regulations are quite severe for large plants, which implies that here even power generation based on "dirty" fossil fuels like heavy oils and certain coal qualities would give fairly small amounts of emissions to the atmosphere. Among the emissions regulated at power generation are sulfur, which in the form of sulfur oxides contribute to the acidic impact on the environment. The sulfur oxides, generally denoted by SOx, are commonly quantified as SO_2-equivalents, in a way similar to the quantification of nitrogen oxides (NOx) as NO_2-equivalents.

Together, nitrogen and sulfur oxides are commonly referred to as acid gases, to which the acidity of the atmosphere resulting in the increasingly acid rains could be referred. The measure used to quantify the acid gases is NO_2-equivalents. The addition of NOx and SOx is commonly made on a molar basis, where the weight quantity of SOx in SO_2-equivalents is multiplied by the factor 1.25 to be transferred to NO_2-equivalents.

2.2.2 Unregulated emissions

The increasing interest in unregulated emissions is based on the insight that the broad regulated groups of hydrocarbons (HC), particulates, and to some extent even nitrogen oxides (NOx) are inadequate to describe relationships between emissions and their effects on health, environment and climate. The growing knowledge of which chemical compounds are responsible for effects such as ozone formation, impairment of visibility, acid rain, plant damage, cancer risks, etc will most certainly lead to supplementary legislation to limit emissions of some compounds. Indeed, vehicle exhaust limits have already been adopted for benzene and formaldehyde in California (Table 2.1). Other compounds of interest are light olefinic hydrocarbons (alkenes), monoaromatics, n-hexane, aldehydes, oxidants like ozone and PAN (peroxiacetylnitrate), polycyclic aromatic compounds (PAC), nitrogen dioxide and dinitrogen oxide, alkyl nitrites. For some compounds maximum levels in ambient air have been determined in air quality standards issued or recommended by the World Health Organization (WHO) or national agencies.

For gasoline, benzene and exhaust gas benzene precursors (other monoaromatics) and gaseous and volatile olefins (urban ozone precursors and cancer initiators) are the most critical compounds. PAC with genotoxic properties are also of interest.

The genotoxic property of a substance is generally expressed by its mutagenicity. This is measured by the number of mutations (revertants) at exposure to genetically active material, normally in an Ames test with bacteria strains, for instance TA98 with or without added enzyme extracts S9.

For diesel oil its content of PAH (polycyclic aromatic hydrocarbons) is critical for the formation of genotoxic PAC in the diesel engine exhaust gas. The content of sulfur and aromatics is important for the reduction of particulates (and NOx) and to make the use of durable catalyst systems possible. Oils with good ignitability are highly desirable to keep the exhaust gas emissions of hydrocarbons, particles and NOx as low as possible.

Alternative fuels like methanol, ethanol, natural gas and propane are characterized by having low ozone forming potential and low genotoxic properties. In exhaust gases from engines operated on these fuels, emissions of benzene and fuel derived PAC with genotoxic properties are (completely) eliminated and their urban ozone potential is low. Alcohols give emissions of aldehydes, which must be controlled by catalyst systems. Such systems could well be used as the fuels are sulfur free and do not generate particles. Ethanol generates gaseous alkenes (ethene, propene) comparable to what a diesel oil fueled engine emits. Propane generates gaseous alkenes and aldehydes in the exhaust gases on the same level as gasoline. Propane and natural gas fueled engines require operation according to the otto cycle and the use of 3-way catalyst systems to attain sufficiently low emissions of NOx. The future of those engines is thus dependent on the development of such technical systems for gaseous fuels. Unburned methane emissions may give a small contribution to the global ozone formation and to the greenhouse effect.

There is also a potential problem with emissions originating from lubricants that have to be used for the engines dedicated to the various alternative motor fuels.

2.2.3 Greenhouse gases

The emissions of so called greenhouse gases are incompletely known and there is no general agreement on how to calculate them. Carbon dioxide, methane, dinitrogen oxide and ozone give directly radiation absorbing effects in the ratios 1:70:200:1800 per kilogram of respective gas in the atmosphere. An indirect effect is obtained when, through chemical reactions, carbon dioxide and ozone are formed from carbon monoxide and hydrocarbons (including methane) with the assistance of nitrogen oxides, and all these thereby influence the greenhouse effect.

The effects of the emissions also depend on the lifetime in the atmosphere of the respective compound. (This lifetime is preferably defined as the half-life, which is for methane 9 years, CO_2 100 years, N_2O 150 years and ozone 0.2 years.) Small quantities of long-life compounds are thus significant in this scheme. Estimates of the relative effects per kilogram of the respective emission in a time perspective of 100 years are given in Table 2.3 below /45/.

Most of today's natural greenhouse warming depends on water vapour in the atmosphere. It is concentrated in the troposphere but varies considerably with time and location from nearly zero to 2 % by volume. The average residence time in the troposphere is short, about ten days, and the concentration may not be directly influenced by human activities. There seem to be great uncertainty about how water vapour and clouds affect the radiation balance of the earth.

Table 2.3 **Estimates of relative effects of some greenhouse gases**

CO_2 (carbon dioxide)	**1**
CH_4 (methane)	**21**
N_2O (dinitrogen oxide)	**290**
NOx (nitrogen oxides)	**7**
CO (carbon monoxide)	**3**
HC (C_2+; non-methane hydrocarbons)	**11**

The above numbers are used to recalculate emitted quantities of the respective gases to additive numbers in total CO_2 equivalents for each fuel chain studied. They are based on the best knowledge available but this is not very consolidated yet. Just recently, the IPPC (Intergovernmental Panel on Climatic Change) decided to alter the factor for NOx from 40 to 7 /87/.

2.3 Allocating and crediting

In many of the energy chains studied, some subprocesses include larger energy flows than needed for the particular fuel studied. In a crude oil refinery, for instance, diesel oil and gasoline are produced simultaneously and together with other products. It is then natural to distribute the energy inputs for the refining process among the products with due consideration to the processes used for each product. The same principles can be applied to ethanol production from biomass.

The major purpose with the processes considered in this study is to produce motor fuels on a commercial scale with known techniques. Some of them produce several motor fuels as co-products, others yield also other energy products as co-products, while still others give some motor fuel and some by-product not necessarily of energy character. This study deals with plants designed to be energywise self-supporting and aiming at producing substantial quantities of motor fuels to the largest possible extent.

Energy inputs and emissions are allocated energywise between energy products when applicable. By-products of non-energy character, e g feed protein, are credited for the substitution of (fossil) energy used elsewhere, e g for conventional production of feed protein. For energy products, energy use is allocated to each product according to its energy content but with consideration taken to which subprocesses are required for each product.

There are many possibilities of crediting energies and emissions, but none is undisputably correct. The best one to use depends on the (local) conditions. In /46/ where large-scale production of bioethanol is studied, three major principles of crediting co-products with energy and CO_2 values were established:

No co-product credits: It is assumed that no energy or CO2 credit can be assigned to the co-product. (This is the lower end of the range.)

Substitution credits: It is assumed that the co-product substitutes for another product in its "most likely" use and that the energy and CO_2 credit is therefore equivalent to the estimated energy and CO_2 expenditure in the manufacture of that product.

Thermal credits: It is assumed that the co-product is used as fuel and that energy and CO_2 credits are assigned in accordance with its calorific value. (This is the high end of the range.)

2.4 Fuel energy to transport work

Fuel consumption and emissions vary among vehicles according to many parameters of design character. For the user/keeper of the vehicle it is of interest to know the fuel energy required to drive the vehicle a certain distance. This energy quantity depends not only on the basic design parameters of the vehicle, but also on the way it is driven and the load it carries. Furthermore, for flexible fuel vehicles there could be a different fuel energy demand between possible fuels.

When it comes to transport work, however, the relevant point is the fuel energy required to transport a certain pay-load a certain distance.

In order to enable the reader to get an idea of the consequences to energy balance and environment of the utilization of the fuels to get transport work made, we give typical energy consumption values and emission values for three model vehicles (a passenger car, an urban bus and a medium heavy distribution truck) for each fuel. For comparison, reference fuels are needed. These will be lead-free gasoline of average European type (see appendix 3.1) for the car and low sulphur grade standard diesel oil (any of the D qualities of appendix 3.1 but with only 0.05 weight % sulfur) for the bus and the distribution truck.

The energy consumption of vehicles depends on (among other things) the engine, the drive train, and the driving pattern. For proper comparisons of results from operating vehicles on various motor fuels, the vehicles/engines should, if possible, be compatible with respect to technical maturity and the driving patterns should be the same.

For the reference fuels the conversion of motor fuel energy to transport work via dedicated engines and drive trains are set to be 35 % in the heavy duty diesel engine bus operation (German Braunschweig testing cycle) and 18 % in the light duty otto engine car operation (weighted result from the American federal test procedure, FTP 75 and highway fuel economy test, HWFET).

The consumption of reference fuel per vehicle kilometer for the chosen typical vehicles and their weight parameters are set to be as stated in Table 2.4 below. It has to be observed that the weight stated is the actual operational weight of the vehicle and that the payload is meant to be a reasonable value for the actually utilized transport capacity of the vehicle and not necessarily its maximum payload. This utilized payload is included in the operational weight of the vehicle.

Table 2.4 **Data for model vehicles**

vehicle	curb weight	payload max.	payload average	fuel consumption/ energy use
car	**1.2 ton**	**0.4**	**0.12 ton**	**0.105 l/vkm of gasoline** **≈ 3.4 MJ/vkm**
truck	**5 ton**	**8**	**5 ton**	**0.28 l/vkm of diesel oil** **≈ 9.9 MJ/vkm**
bus	**11 ton**	**6**	**1.2 ton**	**0.45 l/vkm of diesel oil** **≈ 16.0 MJ/vkm**

The above consumption figures reflect the higher values, which are experienced at normal working conditions and at other driving patterns than in the engine testing laboratory. Figures from the latter facilities, which quite often are quoted, serve mainly as a starting point for the estimate of the actual consumption figures, which eventually are recorded for real operation in traffic.

2.5 Reference emissions

The reference emissions for the use of the vehicles are based on measurements in the engine testing laboratory corrected for other driving patterns, colder weather and deteriorations with increasing age. They are collected from SNV 3840 /51/ for cars with a three-way catalyst and from VTI notat T 84 /52/ for cars without catalyst and for the heavy vehicles (with SNV 3285 /53/ as complement). For the heavy vehicles, the deterioration factors have not been considered, since the measurements concern vehicles of varying age.

Table 2.5 **Reference emission values for the typical model vehicles of middle age**

Vehicle; fuel	CO	HC	NOx	Part	CO_2
	g/vkm				
car without cat. gasoline	**21**	**1.8***	**2.2**	**0.05**	**256**
car with cat. gasoline	**7.6**	**0.9****	**0.4**	**0.005**	**256**
distr. truck diesel oil	**4.5**	**1.6**	**14**	**1.8**	**745**
urban bus diesel oil	**2.3**	**1.7**	**20**	**1**	**1200**

* +1.3 by evaporation
** +0.05 -"-

Some of the above figures could be up-dated as there are better engine/vehicle-combinations available. This is not done since the figures are meant to be some kind of reference for the emission potential of the alternatives. It should also be noticed that the particle figures for the heavy duty vehicles derive from a typical European diesel oil (not more than 0.2 weight % sulfur in average over the year).

In order to estimate the effects on the environment and on human health the above emissions are insufficient. They have to be supplemented by analyses concerning ethene/propene, benzene, aldehydes, PAC and mutagenic activity. However, only little measurement data are available for these, especially for vehicles with high mileage and for heavy vehicles and hence the influence from ageing cannot be estimated yet. In Table 2.6 below typical values from measurements of mentioned substances at relatively new vehicles and engines are presented.

Table 2.6 **Some measured emissions from relatively new vehicles**

\Substance \ Vehicle\	ethene/ propene mg/vkm	benzene mg/vkm	aldehydes mg/vkm	PAC µg/vkm	mutagenicity rev/min
car without cat. gasoline	150	100	40	200	75
car with cat. gasoline	15	6	7	4	2
urban bus without cat. diesel oil	100	15	170	200	300+

The estimated emissions indicate as far as possible the future levels that are judged to be achievable with identified techniques concerning fuels, engines and, most importantly, catalytic clean-up systems. It seems important to use this view for decisions in the long term. The data base for new alternatives is often incomplete, which is natural for techniques under development.

Examples of new techniques not yet fully appreciated are the use of preheated catalysts for the lowering of cold start emissions and the maintaining of operating temperature at low engine load.

3. ENERGY

In the study (reformulated) gasoline and diesel oil, propane (LPG), methanol (fossil and bio-origin), bio-ethanol, methane (natural gas and biogas), vegetable oils, hydrogen and electricity have been included. Fuel chains from production of feedstock to delivery of finished fuel to the vehicle tank (battery) and end use are described and analyzed in energy terms. Emissions and health and environmental impacts are treated in chapter 4.

3.1 Diesel oil, gasoline

Diesel oil and gasoline are unavoidably produced together at the refinery although the ratio can be widely varied. Usually some LPG and heavy fuel oils are included in the product mix. In theory there is from the energy point of view an optimum ratio between diesel oil and gasoline in a system, including the end use in otto and diesel engines. This optimum ratio is probably different from today's ratio in typical refineries, which produce an excess of gasoline. In this study a product mix of light products (gasoline, nafta, LPG), middle distillates (diesel oil, light fuel oil, jet fuel) and heavy products (heavy fuel oils) in the ratios 2:2:1 is used as typical for the Swedish market and many European markets.

The fuel chain from crude oil via finished motor fuel to the vehicle includes extraction of the crude with some primary treatment, transport to refineries, refining to the required mix of products, transport to distribution terminals and final distribution to retailer (gasoline stations or customers with own storage and dispenser). Intermediate storage occurs at every stage.

At the crude oil wells, some gas is flared, or vented. Total flaring in the world is estimated to be up to 100 Gm^3/year corresponding to 4 % of the energy content of the recovered crude oil. In areas with severe emission restrictions, such as the Norwegian sector of the North Sea, the flaring is low, 0.5-0.9 % of the total recovery, but it is estimated to 1.7 % for the British sector/16,45/. In most large production areas of the world flaring is probably considerably higher.

Energy usage for the extraction and associated primary treatment to obtain a shipable crude from off-shore fields in the North Sea, is according to one source 1.8 % of the energy of total extracted hydrocarbons, but in the range 1-2.7 % according to other sources. Stabilization of the crude by separation of LPG and lighter gases is included in the treatment, requiring about 0.5 % of the energy recovered. The fuel used is mostly natural gas (wet gas) and a small amount of diesel oil. Some releases of hydrocarbon vapors occur at the wells.

In this study a figure of 3 % based on final products is used for oil extraction including flaring.

Transportation of crude oil to refineries or consumer areas is by pipeline (over land or from off-shore fields near the coastline) or by sea tankers. Over long distances supertankers, >250,000 dwt, are used requiring 0.6-0.7 % of the energy content of the load for fueling (as bunker oil and diesel oil). Smaller tankers, about 40,000 dwt, used for short distances, require an equal percentage for the transport/103 in ref.63/. The fuel consumption of motor driven pumps in pipelines is of the same magnitude.

In refineries there are small losses of hydrocarbons, 0.1 % according to Concawe /43/, in connection with unloading, refining, storage and loading by evaporation, fugitive emissions and in waste water. Another investigator/45/ found 0.2-0.3 % evaporative loss from loading and unloading shuttle crude tankers from off-shore fields to refineries.

Energy is required to run the refinery operations and processes /8 in ref.63/ in the form of fuel (refinery gases, fuel oil, coke), steam and electric power for pumps, compressors, etc. The energy usage increases with increasing share of light products (gasoline, jet fuel, diesel oil) and increasing quality of the products, for instance high octane gasoline, high cetane, low sulfur diesel oil. Gasoline requires more processing than most other products and several processes are mainly or solely devoted to the production of gasoline components (catalytic cracking, reforming, isomerization, alkylation, polymerization, etc). The energy usage has to be split and allocated to each group of products (light, intermediate, heavy) to obtain fairness, which means that gasoline has to carry a greater part of the energy used and heavy products less than average.

For the refinery with the product group mix of 2:2:1 mentioned above and assuming electricity and steam produced in a refinery co-generation unit, the total energy usage is nearly 7.5 % of the crude input (8 % based on product output). Gasoline processing accounts for 68 % of the energy usage, middle distillates for 25 % and heavy oils for 7 %, based on the split between the different units according to Table 3.1.1.

Table 3.1.1 Energy usage split in refinery units for different product categories. In percent.

Unit / Product	All	Light	Middle	Heavy
Distillation	26	10.5	10.5	5
Catalytic cracking	26	17	9	-
Desulfurization	2	0.5	1.5	-
Reforming	23	23	-	-
Isomerization	9	-	-	-
Alkylation	4	4	-	-
Visbreaking	3	0.5	0.5	2
Other	7	3.5	3.5	-
Total	100	68	25	7

The allocation thus results in an energy usage for each group of products as percent of the product energy content as follows:

Light	13.5 %
Middle	5 %
Heavy	3 %

Improved energy efficiency in the refineries will lower these figures somewhat but increased quality demands counteract that and the improvement difference between gasoline and diesel oil is likely to be less.

Reformulation of gasoline to the type now being discussed in the U.S. (appendix 3.1; typically lower in volatility, benzene, aromatics, olefins and containing oxygenates) involves changing the utilization ofthe refinery processes, which can sometimes decrease and sometimes increase the processing energy usage. Blending with oxygenates such as the ether MTBE is a key element in the reformulation. This contributes to increased energy usage, as methanol is one of the feedstocks for MTBE, and the other building stone, iso-olefins, may have to be made from saturated hydrocarbons, alkanes, by dehydrogenation. Blending with oxygenates, being very high-octane components, also means, however, both less volume demand of hydrocarbons and less octane demand, resulting in lower refinery runs and lower conversion by cracking and less severe reforming, to which limitation on the content of aromatics contributes. Reduced content of benzene, by less volatile reformer feed, and lower volatility, particularly by reduced content of light olefins, will increase the demand on processes to use and up-grade light hydrocarbons by isomerization, etherification and alkylation. Reduction of the content of heavy, aromatics by hydrogenation may be required.

Reformulation of the gasoline will require new investments in refineries and make the gasoline more expensive. It is not clear how the energy usage will be affected but it is likely to be somewhat increased. Until studies on this matter are available a preliminary estimated, 15 % increase is applied for total energy usage and allocations compared to the present gasoline in Table 3.1.1. This results in increasing energy use for gasoline refining from 13.5 % (p.17) to 15.5 % on the basis of product energy content.

It must also be noted that European gasolines differ from US gasolines by having higher contents of aromatics and benzene and lower content of olefins. Reformulation to similar composition as discussed for the US gasoline might therefore have a greater impact on energy usage in Europe.

The production of urban diesel oils, now being being marketed in Sweden (appendix 3.1), involves severe hydrogenation to reduce PAH, total aromatics and sulfur. Such hydrogenation (possibly including hydrogen manufacture) is one of the most energy consuming processes in the refinery and may nearly double the energy usage, increasing the 5 % in the table above to about 9 % for a diesel oil with sulfur content below 10 ppmw, aromatics content below 10 vol% and extremely low content of polycyclic aromatic hydrocarbons (PAH).

Distribution from refineries occurs by coastal or barge shipping on waterways or by pipeline over land to terminals and further on by road tankers to dispensing stations to customers. Energy usage (diesel oil) in this transportation chain is ≤1 % of the energy content of the fuels distributed. In the distribution of the gasoline there are evaporative losses, which have been estimated to be 0.6 % of the gasoline but may have been higher because of the higher volatility of the marketed gasoline than assumed. Closing of the system by improved sealing and use of vapor recovery systems at the loading of ships, storage tanks, road tankers and vehicle fuel tanks will reduce this loss by at least 70 %.

In summary energy usage including losses in the whole chain from crude oil recovery to filling the vehicle tank with the finished fuel is summarized in Table 3.1.2 on the basis of one MJ of motor fuel. The energy resource use for diesel oil/gasoline is also illustrated in Figure 3.1 and 3.2. These as well as the following figures of this chapter are centred around the fuel energy unit in the tank represented by 100 % in the middle (more or less shaded) box state of the figure. From the tank state, the energy usage as in a summarizing table (here Table 3.1.2) is built up to the total energy resource use box at the left of the diagram in steps specified in the table and corresponding to the first four general steps/subprocesses of section 2.1. The energy use of each step is quantified by the slope of the line "roofing" the specific step. In the other direction, towards the transport work box at the utmost right of the diagram, the two general steps of section 2.1 (no 5 and 6 there) are merged to one step only, called end use. This is because the emphasis of this study, in line with the intentions, is placed on the fuel handling process antecedent to fuel use in vehicles. The end use process as explained in section 2.4 is based on typical efficiency figures for relevant engines/ motors at specified driving/testing schemes.

Table 3.1.2 Energy usage in the fuel chain crude oil to gasoline/diesel oil.

Step	**Energy use, MJ/MJ_{fuel}**			
	Gasoline		**Diesel oil**	
	standard	**reformulated**	**standard**	**urban**
Crude oil recovery	0.03	0.03	0.03	0.03
Ocean transport	0.007	0.007	0.007	0.007
Refining	0.135	0.155	0.05	0.09
Distribution (incl. evaporative losses)	0.016	0.014	0.01	0.01
SUM	0.19	0.21	0.10	0.14

The figure 0.03 for crude oil recovery is considered to be a best case value. World average today is higher due to flaring.

The end use of motor fuels is illustrated in three examples for a passenger car (PC), a medium heavy duty truck (MDT) and a bus in urban transit traffic with the following characteristics (from 2.4) on typical weight, average payload and fuel consumption per vehicle-kilometer (vkm).

	Curb weight	Payload, max.	average	Fuel consumption	
PC	1.2 t	0.4	0.12 t	0.105 lit/vkm gasoline	≈ 3.4 MJ/vkm
MDT	5 t	8	5 t	0.28 lit/vkm diesel oil	≈ 9.9 MJ/vkm
Bus	11 t	6	1.2 t	0.45 lit/vkm diesel oil	≈ 16.0 MJ/vkm

The total resource use in energy terms for each category will thus be as shown in Table 3.1.3. The use of catalytic exhaust gas clean-up systems increases the fuel consumption somewhat (already included for PC with 3-way catalyst; oxidation catalyst assumed for diesel engines), we assume 4 %, because of higher flow resistance compared to the muffler. This increase is not always visible as the catalytic systems are often introduced together with new, more efficient engine generations. The increased consumption figure is always used in the following when catalysts are installed.

Table 3.1.3 Total resource use for three catalyst equipped vehicles using gasoline or urban diesel oil.

PC	**4.1**	**MJ/vkm**	**(gasoline)**
MDT	**11.7**	**MJ/vkm**	**(diesel oil)**
Bus	**19.0**	**MJ/vkm**	**(diesel oil)**

3.2 Propane (LPG)

Automotive liquid petroleum gas (LPG) is defined by its property that it can be stored and handled in the liquid phase under moderate pressure at ambient temperatures. Standards have been proposed for a test vapor pressure requirement depending on the season. In practice autogas specifications for colder regions (Scandinavia, North America) prescribe minimum 95 vol% (gas phase) of propane, whereas mixtures of propane and butanes are marketed in Europe. Unsaturated hydrocarbons, olefins and particularly dienes, are limited to avoid formation of deposits and also because they have lower octane numbers. Varying composition is a disadvantage with the present fuel/air preparation systems. More sophisticated ones are required for good fuel/air-ratio control and could also accomodate varying fuel compositions.

There are two major routes to propane, recovery from gas in connection with crude oil and natural gas extraction and from the refining of crude oil to gasoline. The latter is the major source in Western Europe. The Middle East area is the major origin of surplus propane for export.

Gases dissolved in oil under pressure are removed to stabilize the oil for shipping under ambient conditions. The propane content of stabilized oil is low, about 0.1 %. Higher gaseous hydrocarbons in wet natural gas must be reduced to prepare the natural gas for pipeline transport. The gases removed are fractionated by distillation at low temperature and/or under pressure to yield liquid pentanes and higher, butanes, propane and possibly ethane.

In the refinery the naphta reformer is the main source of propane but there is a contribution also from the catalytic cracking process. Cracking processes, however, mainly yield unsaturated, gaseous hydrocarbons (olefins), from which propane is separated by distillations. The olefins are utilized by polymerization, alkylation and/or etherification to produce liquid, high-octane gasoline components (high-cetane middle distillate is another, not yet commercially used possibility).

Energy use to produce propane should carry its proportional part in the oil and natural gas extraction and primary treatment to obtain shipable intermediates. Propane should also carry its part for the separations in wet gas terminals at oil fields and in the natural gas chain. Refinery propane should share the energy usage in parts of the gasoline production steps. It is estimated to be a little lower, 10 %, than for gasoline (13,5 %) as not all gasoline component forming processes are involved.

Shipping of propane in big volumes or over long distances is accomplished by ships with insulated tanks for cold, condensed liquid. Shipping over shorter distances from refineries or gas terminals to distribution terminals occurs as liquid in tanks under pressure. At the distribution to dispensing pumps of the end users rail and road tankers for transport under pressure are used. Transport of propane is estimated to use about twice as much energy, compared to gasoline, because of lower energy density and use of smaller ships and heavier pressure tanks.

Large scale storage of propane occurs most suitably as cold condensed liquid in insulated tanks or, preferably in underground caverns. Pressure tanks are used for storage in smaller scale. Losses during storage are considered negligible.

Dispensing of propane to vehicles occurs as liquid propane from a pressure storage tank via a meter to the pressure tank on board the vehicle. When disconnecting the nozzle from the adapter of the vehicle a negligible amount of propane (≈25 mg) is vented to the atmosphere.

In summary, energy usage in the whole chain from crude oil or natural gas revovery to filling the vehicle tank is compiled in Table 3.2.1 using data from the other chains. See also Figure 3.3.

Table 3.2.1 **Energy usage in the the fuel chain crude oil/ natural gas recovery to automotive propane.**

Step		Energy use MJ/MJ$_{propane}$	
		Field gas propane	Refinery propane
Gas/oil recovery		0.03	0.03
Wet gas terminals		0.02	-
Sea transport		-	0.007
Refining		-	0.10
Sea trp. to terminals		0.015	0.01
Land distribution		0.015	0.015
	SUM	0.08	0.16

End use of propane presently occurs in otto engined vehicles, most often converted gasoline and diesel engines. (Engines with direct injection of liquid propane and using diesel cycle operation (with ignition assistance) might be available in the future.) Light duty vehicles with dedicated propane engines may achieve equal or higher efficiency compared to gasoline-fueled engines. Converted heavy duty engines at present suffer from lower efficiency compared to the diesel oil-fueled engine. About 10 % higher fuel consumption in energy terms has been assumed for future dedicated and optimized vehicles, although the development has today not reached this level but higher figures are often measured in tests with current designs (converted gasoline and diesel oil fueled engines).

For the three model vehicles exemplified above (2.4) the following changes in fuel consumption and resulting energy usage figures are assumed compared to gasoline and diesel oil operation (with 4 % increase due to use of 3-way catalysts needed to fulfil future exhaust limit goals).

PC	-9 %	≈	3.1 MJ/vkm
MDT	+10 %	≈	11.3 "
Bus	+10 %	≈	18.3 "

The total resource use for the three vehicles is shown below.

Table 3.2.2 **Total resource use for three vehicles powered by dedicated propane-fueled otto engines.**

	Field propane	Refinery propane
PC	3.35	3.60 MJ/vkm
MDT	12.2	13.1 "
Bus	19.7	21.2 "

The maximum payload allowed will be somewhat reduced with propane because of the bigger fuel volume and weight of the fuel tank required for the same driving range. The weight penalty for buses is about 350 kg. A 5 % greater number of buses would be needed to for unchanged transport capacity, and the average payload would also be reduced. At the average payload the fuel consumption would be slightly higher (≤1 %) because of the increased weight. This is assumed to be considered in the fuel consumption figures used.

3.3 Methane

Methane (CH_4), the lightest hydrocarbon, is the main constituent of (fossil) natural gas as well as of "natural" gas originating from biodegradation of organic matter, commonly called biogas. Natural gas is dealt with in several technical forms, more or less densified compared to the gas under normal temperature and pressure (NTP). Major forms of natural gas are pipeline gas, LNG (liquefied natural gas) and CNG (compressed natural gas), out of which CNG is the possible commercial vehicle fuel product. LNG is an alternative to pipeline gas, that is a transportation form. Also biogas is, as a possible motor fuel product, considerably compressed.

3.3.1 Natural gas

In this section mainly CNG will be dealt with, but a small paragraph on LNG is included.

CNG (Compressed natural gas)

The fuel chain of natural gas is relatively uncomplicated. The processes that require energy and lead to emissions are mainly: extraction, processing, distribution and the end use compressor stage.

However, energy need does vary between different fuel chains. For example the flaring and losses of natural and associated gas is considerably lower in the North Sea compared to extraction in the Middle East. As the Swedish natural gas supply is based on delivery from the North Sea most figures will mainly be based upon that system even if global figures will also be considered.

Energy need for off-shore extraction and preparation of oil and gas in the North Sea is estimated to 1.8 % in one study. Other sources claim that the energy need for the extraction process of natural gas ranges from almost negligible values to 5.5 % of the energy in produced fuel /4,10,16,24/. The lower estimates comes from a production site where the gas flows from the well at high pressure. This situation must be seen as a special case, and at most extraction sites it is necessary to provide energy to prepare the gas for pipeline transfer to terminal for processing. On the other hand the higher value seems unrealistic and it probably includes large flaring losses.

A more realistic value could therefore be 3 % of the produced fuel energy, which includes flaring losses and leaks connected to the extraction process.

The next step in the fuel cycle is processing where energy need is highly dependent upon the quality of the extracted gas. A sour gas requires more energy to be desulphurized than a sweet gas but it is also necessary to separate higher hydrocarbons and water. Natural gas from some fields in the North Sea is of such a quality (dry gas), that it does not have to be prepared at all, not even sweetening has to be done. On the other end there is extracted gas which has very high sulphur content (extreme 60 %!). 2-3 % of the product fuel energy is mentioned as the required energy /10,16/, and for the Swedish case it is even lower. Thus 2 % will be considered a resonable figure.

Distribution of natural gas takes place in pipelines and the gas is pushed through by compressors. Those are normally powered by natural gas and most sources say that 2 % of the energy is needed for this activity /10,16/. However, one source claims that the energy need is 5 % /34/. This depends on the length of the distribution line, but also on the pressure obtained from the well-head. 2 % will be used in the following calculations. The figure is based on a normal distribution length of 1000 km.

The last part of the full fuel chain is the high pressure compression up to 200 bar. The compressors are generally electrically powered and require electricity amounting to 3-4 % of the product fuel energy. The energy need depends on the final pressure. If the compressed gas is used for slow fill of vehicles it will be sufficient with a lower energy demand, 3 %, to reach the maximum pressure of 200 bar used in vehicle cylinders. An alternative is to use a fast fill solution which means that the compressed gas is stored in a high pressure bank. When a vehicle is to be filled up it is connected to the bank and a pressure equalization takes place. In order to minimize the size of the bank its pressure has to be higher than the desired vehicle tank pressure. A normal value is 250 bar and the energy consumption is then estimated to 4 % of the product fuel energy.

If the electricity needed for the compression work is generated in a natural gas power plant, as defined in section 2.1.2, the primary energy need will be in the range of 6.4 - 8.5 % depending on slow fill or fast fill principle. As a weighted average figure 7 % will be used.

The compression energy demand could be reduced if the natural gas is taken from the main pipeline at a higher pressure, i.e. the gas comes to the compressor with a pressure of 30-50 bar instead of just above atmospheric pressure. In that case the energy need could be reduced significantly. However, this is very seldom used and will not be considered in the following calculations.

Along the whole chain there are also losses of gas (CH_4) due to leakage in for example pipelines. Leaks also occur at the wellhead at production sites. Measurements quantifying wellhead leaks are not available. Some sources indicate that leakage and venting from natural gas extraction and distribution should be about 2-3

% of production in Europe and 3-4 % on a global average. The major part occurs in the tail end of a net.

Leaks can also occur from pipeline compressors and plant machinery. Those losses are estimated to 0.7 % of end use. However, recent figures from the natural gas industry claim that total emissions are not more than 1 % of production. For new supply systems, leakage rates of 0.05 % should be achievable. The leakage rate from the natural gas supply system to Sweden from the North Sea via Denmark is estimated to be around 0.1-0.5 %.

Summarizing the methane leakage figures, it is likely that losses for newer natural gas systems are less than 1 % of end use. For older systems, though, there still might be bigger losses. A loss of 1 % is included in the energy need figures of the extraction and distribution processes. The loss is assumed to be equally distributed among the extraction, processing and distribution steps. In the future it is likely that the leakage rate will decrease because older pipeline systems are replaced.

The energy requirement for the natural gas fuel chain is summarized in Table 3.3.1 below. See also Figure 3.4.

Table 3.3.1 Energy usage in the natural gas (CNG) fuel chain

Step	**Energy use** $\mathbf{MJ/MJ_{CNG}}$
Extraction/preparation	**0.03**
Processing	**0.02**
Distribution	**0.02**
End compression	**0.07**
Total	**0.14**

LNG (Liquified natural gas)

Commercially CNG is much more developed and used than LNG. The main reason for this is probably the difficulties of handling and storage of the liquefied gas in cryogenic bottles. The following description will therefore give only a brief view.

The first steps of the fuel chain are almost the same for LNG as for CNG. Extraction/preparation and processing require 2 % each of the energy in the produced fuel. So far the energy demand is a bit lower for LNG than for CNG. The main energy required for LNG is for the gas liquefaction process. In modern plants 9-10 % of the fuel energy is needed for this purpose /65/. Other processes requiring energy and contributing to losses are storage, ocean shipment and regasification. Together these processes demand 2-7 % of the fuel energy and the losses are estimated to be 1-2 %. The losses depend on how long the fuel is stored or transported as a liquid, since there are always boil-off losses from the cryogenic tanks (0.15 % per day). These losses are used as fuel in the ship's engines.

Alltogether this makes a total energy use of about 20 % for the full fuel chain of LNG. In comparison to the 14 % of CNG this is a high fuel chain energy use. Adding this to the expected practical difficulties with cryogenic tanks in vehicles it is fully understandable that CNG is the preferred vehicle fuel.

<u>End use</u> of CNG as a motor fuel normally takes place in otto engines. For the use in heavy vehicles the diesel engines have to be converted to the otto cycle. As the otto cycle generally has a lower efficiency compared to the diesel cycle, methane gas for heavy vehicles will have a lower efficiency than diesel oil in diesel engines.

The reduction of the efficiency compared to diesel engine powered heavy vehicles is today fairly high but field trials have indicated that ongoing engine development will achieve a reduction as low as 10 % of the efficiency. This figure does not include the increased fuel consumption due to the heavier fuel tanks. For a normal bus this figure is estimated to be ~1.1 % increase for a CNG system compared to diesel oil (appendix 4.3).

For the passenger car there is no efficiency reduction for CNG use and it is even possible to obtain a higher efficiency due to the higher octane number of methane gas compared to gasoline. This potential is estimated to give a better efficiency by 10 % for the methane gas engine /69/. For the truck and the bus an extra 4 % of efficiency reduction will be experienced at the usage of a catalytic system (TWC).

Compared to the energy use for gasoline and diesel oil powered vehicles the following figures are thus expected for the model vehicles:

- passenger car:	3.1 MJ/vkm
- medium duty truck:	11.5 MJ/vkm
- urban bus:	18.5 MJ/vkm

Total resource use, including the energy need for the fuel cycle of compressed natural gas, will then be as given in the following table.

Table 3.3.2 Total resource use for three vehicles powered by dedicated natural gas (CNG) fueled otto engines

PC	**3.5 MJ/vkm**
MDT	**13.1 MJ/vkm**
Bus	**21.1 MJ/vkm**

3.3.2 Biogas

Biogas can be produced out of a large variety of sources as long as they contain organic material. Examples of such sources are municipal sewage, waste dumps (land fills), manure, agricultural waste, and energy crops. Depending on the source, the composition of the gas will differ but the main component will always be methane.

Like all the bioproduced fuels mentioned in this report it is possible to obtain the fuel as a secondary product from the main product. For example, when sewage is treated at the plant biogas is produced as a bonus. However, it is not realistic to calculate with a bigger number of vehicles supplied with gas from sewage treatment plants. Only energy crops have the potential for large volumes of fuel and thus to be introduced as a motor fuel source on a big, commercial scale.

This means that a biogas fuel chain must start with the cultivation of biomass and the chain could then be defined as:

- cultivation/harvesting of a suitable crop
- transportation and handling of biomass and residues
- microbiologic conversion
- purification/compression
- distribution.

The following example of a biogas fuel chain is based on lucerne as the original crop. The biogas process takes place in two steps which gives a better output rate than the normal one step method. The former can achieve 12.6 GJ/ton dry substance /32/, corresponding to a biogas energy yield of about 70 % of the assumed energy content (LHV) of 18 MJ/t biomass-DS. Unconverted organic matter and energy losses thus amount to 0.44 MJ/MJ biogas from the plant (3 % methane loss later in the process included).

The <u>cultivation and harvesting</u> of lucerne do not need as much energy as for example wheat. Actually, the energy demand is in the same range as for Salix /75/. The yield from a hectare is about 9.5 ton dry matter per hectare but during the harvest 15 % are lost, which gives a net yield of 8.1 ton dry substance (DS) per hectare /32/. In table 3.3.3 below, the energy use per net ton as experienced is reported.

Table 3.3.3 Energy use for the cultivation and harvesting of lucerne in MJ/ton DS

Fuel	
seed	**74**
harvest + transport	**316**
Sowing seeds	**4**
Fertilizers	**50**
SUM	**444**

Including a 3 % methane loss in the process as described for the conversion step later, the energy use for the cultivation and harvesting of lucerne requires thus about 4 % of the final fuel energy. The energy need for fertilizers is small because lucerne takes all its nitrogen needs from the air. No energy is required for drying since the digester process takes place under wet conditions.

Transportation of the crop to the plant is highly dependent on the distance and a big plant requires longer distances than a smaller plant. However, it is desireable to place the plant as close as possible to the fields where the crop is grown. For a 2 MW plant the energy use for the transportation of the biomass can be less than 1 % of the fuel energy /32/. Producing biogas on a commercial scale would require bigger plants and it would not always be possible to have all the surrounding fields to grow energy crops for biogas production. 3 % is thus considered to be a realistic figure for the transportation energy use.

Handling of the biomass at the production site and internal transports, will require 1.5 % of the fuel energy. Also transportation of residues, i.e. fertilizer, away from the plant will require around 1 % in energy need.

The conversion in the digester process requires the major part of its energy in the form of electricity and the demand is calculated to be 8.5 % of the fuel energy. The energy is used to heat the plant and to give power to the circulation pumps. Generated in a natural gas heated power plant, the 8.5 % of electricity corresponds to 18 % of primary energy.

The last process step in the fuel cycle is the purification and compression of the gas. The purification procedure could preferably be of a PSA (pressure swing adsorber) or a membrane type and the compression will result in a final biogas pressure of 200 bar. An amount of 7.5 % electricity of the fuel energy is required for these two steps. Converted to primary energy this is equivalent to 16 %.

To some extent there is a need to distribute the gas to the consumers. However, as mentioned before a biogas system is probably, based on a more local production and distribution compared to the petrol systems of today. Still distribution to consumers has to take place to some extent and a reasonable figure is that 1 % of the final fuel energy is used for this purpose.

The residue has a value as fertilizer and should thus be credited to the fuel chain. The useable components are mainly /51/;

- nitrogen (12 kg/MWh gas)
- phosphorus (1 kg/MWh gas)
- potassium (7 kg/MWh gas).

The energy used to produce these replaced fertilizers by an alternative method is then credited to the energy balance of the biogas fuel chain. Producing nitrogen requires 11.5 kWh/kg and the figure for phosphorus is 1.7 kWh/kg /66/. This gives the energy balance a total credit of 14 %.

For a case where as much fossil energy as possible is replaced by bioenergy all of the energy demand for process and purification/ compression can be replaced by biogas. During the biogas/digester process there is, besides the need for electricity, also a demand for heat. This makes it possible to burn the biogas in a high efficiency cogeneration unit producing both electricity and heat. The efficiency of such units can be as high as ~ 88 %, but the biogas process cannot consume all the heat that is produced. Mostly it is electricity that is needed in the process (pumps, heat pumps etc) and the heat demand is normally covered by heat exchangers. The electricity efficiency of a small cogeneration unit is about 36 % /68/. About 5 % of the energy demand is estimated to be required as electricity and 3,5 % could be supplied as heat. The total efficiency rate will therefore be ~51 % which leads to biogas demand of 17 %.

During the biogas process including storage of the crop, there will also be a certain loss of biomass, some of which will be lost as methane to the atmosphere. These losses are not very well known. The methane losses from a one-step biogas process with vented premixing tanks for the biomass is said to be about 5 % (energy terms) /78/. A two step process will probably have smaller emissions and 3 % methane losses of final energy output is estimated for the following calculations.

Purification and compression processes need most of the energy as electricity and the efficiency for these steps are therefore estimated to be 45 %. This gives the biogas demand of 17 % out of the electricity need of 7.5 %.

During the purification process, where carbon dioxide is separated from methane, about 3 % of the produced methane is lost (also about 3 % of the energy content of the gas). However, this lost methane can be taken care of and utilized in for example the engines that produce electricity and heat to the digester step. Thus, this will not affect the energy balance of the process.

If biogas from the process is used to serve the plant with energy, the cultivated amount of biomass has to increase to produce the same supply of fuel biogas. The extra amount of energy is 17 + 17 = 34 % and this gives an extra energy need for farming/ harvesting and transportation processes. These processes will now need 5.4 % and 7.4 % respectively. Also the amount of residue fertilizer will increase proportionally to 0.19 MJ/MJ_{biogas}.

The energy usage for the biogas fuel chain is summarized in Table 3.3.4 below and Figure 3.5 and 3.6 for the two cases, fossil and biobased process fuel. Substitution of fossil fuel is possible at all stages in the chain, but in the table transportation energy is still considered to be covered by fossil fuels.

Table 3.3.4 shows that the total energy requirement for the case where the process fuel is biogas changes very little from the fossil fuel case. For the biogas case, the net fossil energy balance even turns out to produce more useful energy than is consumed as fossil fuel, after crediting for the fertilizer by-product. This is because the by-product contains a lot of nitrogen, but lucerne does not need energy demanding nitrogenous fertilizer.

Table 3.3.4 Energy usage in the biogas chain; lucerne growing to methane

Step	Energy usage, MJ/MJ_{biogas}	
Process fuel	Fossil	Biogas
Cultivation/harvesting	0.04	0.054
Transports of crop/residue	0.055	0.074
Biogas process	0.18	(0.17)
" " losses	(0.44)	(0.59)
Purification/compression	0.16	(0.17)
Distribution of gas	0.01	0.01
SUM	0.44	0.14
By-product credit	- 0.14	-0.19
NET SUM	0.30	-0.05

( ) renewable energy, not included in sum

As for most crops, except short rotation forestry (Salix), it is not wise to grow the same type of crop for a long time on the same plot of land. To keep the yields at a high and stable level it is necessary to change crops after a few years and to have a larger area available for this crop rotation.

The total resource use for the three model vehicles is shown in Table 3.3.5.

Table 3.3.5 Total resource use for three vehicles fueled by biogas from lucerne.

Process fuel	Fossil		Biogas		
	Total	Fossil	Total	Fossil	
PC	5.4	0.93	5.8	-0.16	MJ/vkm
MDT	20.0	3.9	21.6	-0.58	MJ/vkm
Bus	32.2	5.6	34.8	-0.93	MJ/vkm

3.4 Methanol

Methanol is predominantly produced from natural gas but some methanol is produced from heavy high sulfur, residual oils, hard coal and lignite. Technology for production from peat and biomass (lignocellusosic materials) is available but is not commercially used (demonstrated commercially for ammonia). Methanol production from natural gas occurs increasingly near the gas fields and not in the consumer areas to avoid the high costs for transport of gas compared to the transport of the product, liquid easy-to-handle methanol.

3.4.1 Methanol from natural gas

The methanol chain starts with the recovery of the natural gas as associated gas at oil fields or at gas fields. Energy usage for the recovery is assumed to be the same as in the natural gas chain (3.3) but there may be less losses by flaring when the gas is used at or near the point of recovery. A figure of 3 % based on final methanol product is chosen. Oil and gas fields with insufficient basis for a gas pipeline or a LNG-plant can be utilized for methanol production with corresponding savings in flaring. Off-shore, floating methanol plants are being built.

Methanol plants preferably use wet natural gas because of the more favourable hydrogen/carbon ratio and higher yields. In the preparation of the gas at the terminal the recovery of LPG and higher hydrocarbons can be omitted with correspondingly less energy usage, or this has to be borne by the products recovered if there is a better market for them. Energy usage for the gas recovery and preparation is therefore somewhat lower in the methanol chain than in the natural gas chain. Leaks in modern systems should be minimal between the gas well and the methanol plant, <0.1 %.

Conversion of the gaseous hydrocarbons to methanol via gasification to synthesis gas, methanol synthesis and purification occurs with a thermal efficiency which is the result of an optimization with regard to the (future) price of the gas, the investment cost, and the economic environment (e.g. financing, carbon dioxide release fee). Modern self-sustaining, gas-based plant can be built for a yield of methanol of about 70 % of the gas input (LHV basis) and produce a small surplus of electricty. The upper limit is about 80 % /22 in ref.63/ and 65 % is a typical figure for today's new plants. Older plants may show figures down to 50 %. The yield in energy terms for oil-based plants is lower, say about 60 %, for coal-based in the range 55-60 %. Lignites, peat and biomass are still more hydrogen-deficient feedstocks and often with high moisture content, and higher yields than just above 50 % cannot be expected.

For gas-based plants a range of yields, 65-80 %, is possible which corresponds to an input of 0.55-0.25 MJ per $MJ_{methanol}$ to run the conversion plant. A mid-point value of 0.40 MJ/MJ (yield about 71 %) is used in the following.

(It should be remarked that the similar technologies allow production from synthesis gas of methanol with higher alcohols, ethanol or hydrocarbons (gasoline, diesel oil). This is, however, not meaningful because of lower motor fuel energy yields and higher costs. Fuel methanol with somewhat lower purity than methanol as chemical feedstock can be produced with a slight advantage in investment cost and yield.)

Transport of methanol from plants near the gas fields occurs by sea tankers or over land by pipeline when the volume justifies this. In the long term and large-scale use of methanol as motor fuel transportation in supertankers and pipelines as for crude oil is foreseen. Transportation fuel energy corresponding to a little more than 1 % of the energy equivalent of the load is used. A small loss with the air displaced during loading is unavoidable without vapor recovery (sometimes used at methanol plants). Losses during transport and storage amount to fractions of a promille and are thus negligible.

Distribution from terminals to end users will follow the same pattern as for gasoline and consumes motor fuel corresponding to somewhat more than 1 % of energy equivalent of the load due to the lower energy content of methanol compared to gasoline. Evaporation losses are assumed to be about one third of those of gasoline due to the lower vapor pressure of methanol and about 0.2 % in a fairly open system. Closing the system will reduce losses as for gasoline.

In summary, energy usage in the entire chain for methanol from the natural gas well to the vehicle tank is shown in Table 3.4.1 and illustrated in Figure 3.7.

Table 3.4.1 Energy usage in the fuel chain natural gas to methanol.

Step	**Energy use, $MJ/MJ_{methanol}$**
Natural gas recovery and preparation	**0.03**
Conversion	**0.40**
Sea transport to terminals	**0.012**
Land distribution (incl. evap. loss 0.002)	**0.010**
SUM	**0.45**

The usage of methanol can occur both in otto engines and diesel engines. In otto engines methanol allows a higher efficiency corresponding to 10 % less fuel consumption in energy terms (range 5-15 % or more depending on degree of optimization). In diesel engines the same or a few percent higher fuel consumption is presumed. In development work and demonstrations M85 or M90 (methanol blended with 15 or 10 vol% gasoline/hydrocarbons) are often used for otto engines and M100 for diesel engines. It is presumed that M100 will ultimately be the fuel of choice to use the full potential of emissions reduction.

For the three vehicles exemplified earlier (2.4) the total resource energy usage is shown in Table 3.4.2. Also the medium and heavy-duty vehicles are equipped with catalysts to fulfil future exhaust limit goals.

Table 3.4.2 Total resource use for three vehicles fueled by methanol from natural gas.

PC	**4.44**	**MJ/vkm**
MDT	**14.9**	**MJ/vkm**
Bus	**24.1**	**MJ/vkm**

The maximum payload allowed will be somewhat reduced with methanol, because a bigger volume and weight of fuel and fuel tank must be carried for the same driving range. For instance for buses a greater number of buses, about 4 %, will be required for unchanged transport capacity, and average payload would be reduced. In theory the fuel consumption should be slightly higher (<1 %) because of the increased weight at average payload but that is considered to be included in the consumption figures given for methanol fueled vehicles.

3.4.2 Methanol from biomass

Methanol may as mentioned be produced from biomasses such as forestry and agricultural residues (wood and straw respectively) or purpose-grown energy crops, e.g. short rotation Salix forests. The fuel chain starts with cultivation and harvest of the lignocellulosic feedstock and transport to central conversion plants (gasification to synthesis gas and methanol synthesis) and ends with distribution to end users at refueling stations.

The cultivation/harvest step has been estimated/66/ to require an input of fossil-based fertilizers, chemicals and motor fuels corresponding to about 6.5 % of the energy in the biomass produced by the photo-synthesis. Tree residues from the forestry would require considerably less as fertilizer input is low. Fuel (diesel oil) for machinery used in silviculture and harvesting would be needed /Danielsson in ref.57/. For figures, see under section 3.5. Transport to a large conversion plant is assumed to need energy corresponding to 3 % of the methanol produced, and the conversion plant itself (energy self-sustaining, no by-products) is expected/82,83/ to operate with a thermal efficiency of 50 % (LHV basis) according to several studies. This translates to a yield of 600 litres of methanol per ton of dry biomass (at 19 GJ per ton). The distribution to the end users proceeds via terminals by coastal shipping, barges or pipeline and road tankers and is assumed to use energy corresponding to 2 % of the fuel transported.

The entire chain from feedstock growing to the vehicle tank is summarized as shown in Table 3.4.3 and Figure 3.8 and 3.9. The chain may be made still less dependent on fossil-based inputs if in the nitrogen fertilizer manufacture the ammonia is produced from biomass with very similar technology as for the methanol.

Table 3.4.3 Energy usage in the fuel chain energy forest/tree residue growing to methanol in the vehicle tank.

Step	Feedstock	Energy usage, $MJ/MJ_{methanol}$ Salix	Tree residues
Cultivation, harvesting		**0.13**	**0.06**
Transport		**0.03**	**0.03**
Conversion incl. losses		**(1.00)**	**(1.00)**
Distribution		**0.02**	**0.02**
	SUM	**0.18**	**0.11**

( )= renewable energy, not included in sum

The total resource use for operating the model vehicles (with the same presumptions as used above, 3.3.1) is summarized below.

Table 3.4.4 Total resource use for three vehicles fueled by methanol produced from biomass.

	Salix		Tree residues	
	Total	Fossil	Total	Fossil
PC	6.67	0.55	6.5	0.34
MDT	22.4	1.9	21.7	1.1
Bus	36.2	3.0	35.0	1.8

3.5 Bio-ethanol

Bio-ethanol is produced by fermentation of sugar or sugars originating from starch or cellulose containing feedstocks. The fuel chain starts with cultivation and harvesting of such energy crops with input of fertilizers, chemicals and motor fuels. Processing to ethanol will be exemplified with grains (wheat) and with lignocellulose (wood) as feedstocks.

Data for growing energy crops are taken from the latest evaluations at the Swedish University of Agricultural Sciences /66, 57/. Data for the grain-based fermentation plant is based on recent engineering work /84/ for a moderate size plant (66,000 m^3/yr) using established technology with continuous fermentation and yielding a dried feed protein as co-product. Data for wood based plants are taken from two sources, a Canadian study /47/, founded on preliminary engineering on the basis of pilot plant work, for the Iogen-process (using enzymatic hydrolysis of the celluloses in aspen wood) and a new joint study in the CASH-project (Canada, America, Sweden, Hydrolysis) for a two stage weak acid hydrolysis process. In the Iogen-plant a small surplus of electricity is obtained as by-product as a result of burning unconverted wood (lignin) in a co-generation unit. In the CASH-plant lignin fuel powder is a major co-product.

For growing wheat an input of fossil based fertilizers, chemicals, fuels and motor fuels are required as shown in the table below expressed as usage of fossil energy for their production per ton of dry grains harvested.

Fertilizers, chemicals, seeds	1,400 MJ/t
Motor fuels	740 MJ/t
Grain drying and miscellaneous	840 MJ/t
Sum	2,980 MJ/t

This translates to 0.34 MJ per MJ of ethanol at a yield of 410 liters per ton of dry grains. For transport to a central conversion plant 0.02 MJ of motor fuel is added. Besides the grain kernels nearly an equal mass of straw is grown. Part of this can with a small additional harvesting and transport effort, 0.03 MJ per MJ ethanol, be brought to the conversion plant and be used as fuel for steam generation.

For growing wood in the form of willow (Salix) in short rotation forests, a figure for input of fossil based fertilizers and fuels corresponding to 6.5 % of the energy content of the dry wood harvested is claimed /66/. This translates to 0.18 MJ per MJ of ethanol at a yield of 274 liters per ton dry wood.

In silviculture to form tree residues as feedstock for alcohol inputs of fertilizers and motor fuels are low, but harvesting requires fuel (diesel oil) for machinery (forwarding, chipping). Based on /57; Danielsson/ the following figures are estimated:

Fertilizers	130	MJ/t wood DS
Motor fuel	440	"

Transport to a central conversion plant requires in the range 100 to 200 MJ of motor fuel per ton of wood-DS depending on the distance, 150 to 300 km roundtrip.

Conversion processes of wheat grains to ethanol require 6,450 MJ per ton of dry grain feed (electricity, heat for conversion, distillation and drying). This requires an input of 7,600 MJ to an efficient co-generation unit. This figure translates to 0.87 MJ per MJ of ethanol.

The conversion plant generates 0.28 ton of CO_2 as a possible by-product and a protein feed product in an amount of 0.41 ton per ton of dry grains. Assuming an energy content of 14 MJ/kg DS for the feed product and 17.5 MJ/kg of dry wheat grains the balance leaves 0.35 MJ/MJ of ethanol unaccounted for.

Using the protein feed product as replacement for other animal feed products (soymeal), the process can be credited with the amount of fossil energy used in the production of this product elsewhere. This credit is, according to two sources, 0.13 or 0.19 MJ/MJ of ethanol /46,105/. A figure of 0.16 MJ/MJ will be used here.

Conversion processes of wood to ethanol require more energy than the grain based process and amounts in the Iogen-process to 9 250 MJ per ton of dry wood or 10 900 MJ as input to the co-generation unit, which burns all the unconverted wood and produces a small surplus of electricity over the process requirements for sale. The process energy usage figure is allocated, equally on energy unit, to both output products, 274 liters of ethanol per ton of dry wood and 0.90 kWh electricity per liter of ethanol. Assuming an energy content of the feedstock (aspen wood) of 18.6 GJ/t DS (LHV) the energy input (together with a small amount of lactose) amounts to 19 270 MJ/t DS, leaving 1 700 MJ/DS as losses not accounted for. The process energy usage (including losses) translates to 1.88 MJ/MJ of ethanol.

In the CASH-process energy requirements (steam and electricity) for an energy-wise self-sustaining plant are covered by combustion of methane (from anaerobic fermentation of organic matter in waste water) and part of the lignin. Figures from the engineering study /85/ show yields of 224 liters of ethanol (in 233 liters of E95) ≈4.70 GJ and net 5.83 GJ of lignin fuel per ton of wood-DS in feedstock tree residues (as pine saw dust). With an energy content of 19.0 GJ/t wood-DS (LHV) the process energy usage (including losses not accounted for) amounts to 0.804 MJ/MJ sum of products.

This energy usage should be allocated to each product according to the energy usage in each subprocess being the final end user of the energy. In shared processes (hydrolysis steps) it is split in proportion to the energy content of the products. Ethanol then has to carry the major burden of the energy usage because it is the final consumer of recovered steam energy (including heat of evaporation) from the lignin drying step. The allocation leads to a process energy requirement of 1.38 MJ/MJ of ethanol and 0.34 MJ/MJ of lignin fuel product.

Considerably improved results may, as is pointed out in the study /85/, be achieved if the plant could be coupled to an existing plant with surplus steam (sulfate pulp mill). This results in increased yields of saleable products (and reduces investments). Improved conversion yields to ethanol may be expected in the future with continued development work.

Distribution of ethanol as motor fuel will follow similar routes via terminals to dispensing stations. The transport distance may in total be somewhat shorter than for gasoline because of more wide-spread distribution of plants. The lower energy content of ethanol compared to gasoline will require distribution of a larger volume but evaporation losses for ethanol are lower and nearly negligible. If energy usage for distribution of gasoline and diesel oil is somewhat less than 0.01 MJ per MJ of fuel it will be somewhat above 0.01 MJ per MJ of ethanol.

In summary energy usage for the entire chain for anhydrous ethanol (E100) to the vehicle tank is shown in Table 3.5.1 and Figure 3.10-3.13 for the various cases on basis of one MJ of motor fuel.

Table 3.5.1 Energy usage in the chain from feedstock growing to anhydrous (E100) or hydrous ethanol (E95) resp.

		Energy usage, MJ/MJ ethanol			
	Feedstock	**Wheat**	**Wheat**	**Salix**	**Tree residues**
Step	**Process fuel**	**fossil**	**straw**	**lignin**	**biogas, lignin**
	Product	**E100**	**E100**	**E100**	**E95**
Cultivation, harvest		0.34	0.36	0.18	0.054
Transports		0.02	0.03	0.03	0.015
Conversion		0.87	(0.87)	(1.88)	(1.38)
" losses		(0.35)	(0.35)	incl. in above	
Distribution		0.01	0.01	0.01	0.01
	SUM	1.24	0.40	0.22	0.08
	By-product credit	-0.16	-0.16	-	-
	NET SUM	1.08	0.24	0.22	0.08

( )=renewable energy, not included in sum

A pre-requisite for bio-ethanol production to be a net motor fuel energy producer, compared to inputs of fossil based goods and fuels, is obviously that biomass based fuels are used at the conversion. Process developments will lead to improved ethanol yields and engineering developments will lead to lower process energy needs at the conversion. A still lower input of fossil energy can occur, if fertilizers (ammonia) are produced from biomass. Credits for by-products as used above can be made as long as there is a market for them. If not, another way of disposal must be used and the crediting will be different.

The usage of bio-ethanol as motor fuel may be as a component in gasoline (about 5 vol% E100, E5-blend) or as neat fuel in diesel engines. In the latter case the water containing azeotrop, E95, (somewhat cheaper to produce) can be used. In the first case the volumetric fuel consumption will not be changed, i.e. ethanol displaces hydrocarbons volume by volume. Used as diesel engine fuel ethanol is consumed with unchanged energy usage, ethanol displaces diesel oil energy by energy. There are experiences supporting both assumptions.

For the three model vehicles exemplified earlier (2.4) the total energy and fossil resource energy (wheat-straw case) usage with bio-ethanol will be as shown in Table 3.5.2. Also medium and heavy-duty vehicles are equipped with catalysts to meet future exhaust limit goals.

Table 3.5.2 Total resource use for three vehicle categories fueled by biomass-based ethanol.

Feedstock	**Wheat**		**Salix**		**Tree residues**		
Fuel	**Straw**		**Lignin**		**Biogas/lignin**		
	Total	**Fossil**	**Total**	**Fossil**	**Total**	**Fossil**	
PC*	**4.12**	**3.87**	**4.39**	**3.87**	**4.12**	**3.85**	**MJ/vkm**
MDT	**25.3**	**2.5**	**31.9**	**2.3**	**25.3**	**0.8**	**MJ/vkm**
Bus	**40.8**	**4.0**	**51.6**	**3.7**	**40.8**	**1.3**	**MJ/vkm**

* with E5-blend

The maximum payload allowed will be slightly reduced with ethanol as fuel because a bigger volume and weight of fuel and fuel tank must be carried for the same driving range. For instance for buses a greater number of buses, about 2 %, will be required for the same transport capacity. In theory the fuel consumption should be slightly higher because of the increased average weight but is considered negligible for the ethanol fueled vehicles.

3.6 Vegetable oil

Vegetable oil is produced from various sorts of oil-yielding plants. The most common oil-plant for vehicle use in North-West Europe is rape and the following analysis will therefore concentrate on the fuel chain to rapeseed oil methylester (RME), which is the final fuel product from rapeseed. The heating value of RME is 32.7 MJ/l and its density at 20°C is 0.88 kg/l. RME can be used only in diesel engines. No alterations of existing diesel engines are needed to use RME.

Cultivation and harvesting is the first step in the fuel chain. This process needs an input of fossil based fertilizers, chemicals (pesticides) and fuels. A normal yield of rapeseed /75/ with 43-45 % oil is about 2.0 ton of dry substance (DS) per hectare after reduction for harvesting losses of about 18 %. In Table 3.6.1 below, the different energy requirements /75/ per net ton for this step are set out. Even the process energy for the preparation of the sowing seeds is included.

Table 3.6.1 Energy use for the cultivation and harvesting of rapeseed in MJ/ton DS

Fuel	
seed	**882**
harvest + transport	**414**
Sowing seeds	**18**
Fertilizers	**3 517**
Chemicals	**270**
SUM	**5 105**

Utilizing a warm pressing method with high yield of rapeseed oil the energy yield for the final fuel is 17.2 GJ_{RME} per ton DS of rapeseed /73/. Thus the energy for the cultivation step of the chain is about 30 % of the final fuel energy.

For transport to a central conversion plant 0.02 MJ/MJ_{RME} (2 %) of motor fuels are added. This is based on an average transport distance of 70 km round trip.

The extraction of raw rapeseed oil is fairly uncomplicated and is done by pressing. The raw oil then has to be refined and finally transesterified in order to get physical properties as much like diesel oil as possible. It is possible to use the raw oil as a vehicle fuel, but it is not suitable for commercial use on a large scale. The pressing step requires 3 % based on the final fuel energy /73/. To obtain a higher output of oil from the seed, an extraction process, where the seed is preheated, is often used in larger plants. The energy required for this step is estimated at 3 % in primary energy. Finally the oil has to be refined (that is degummed, transesterified and possibly hydrogen-ated). The energy use for the degumming procedure is estimated to be about 2 % of electricity, which gives a primary energy need of about 4 % (natural gas). Transesterification requires ~1 % of electricity for pumping/heating /72/, which gives a primary ener-gy need of 2 % (natural gas). In the process methanol is added but also glycerin is obtained as a co-product in the same quanti-ties. The energy needed for the production of methanol is 2 % of finished fuel energy. Also the energy requirements to produce glycerin is estimated to be of the same size, which is credited to the chain.

Note! It has not been possible to estimate the losses of energy contained in the feedstock but not accounted for as rapeseed oil and co-product. The rape cases therefore are not quite comparable to the other cases.

End distribution takes place with tank trucks and approximately 1 % will be needed for this activity.

The process energy demand, which sums up to 0.14 MJ/MJ_{RME} (see above), is normally catered for by fossil fuels but can fairly easily be replaced by bioenergy, for example Salix, which is a short rotation forestry product. As described for ethanol the energy need for Salix is 6.5 % of the energy in the wood (appendix 4.5). Of the 0.14 MJ/MJ_{RME} required from process fuel, some 0.09 caters for the 0.045 demand of electricity, 0.03 is required as heat, and 0.02 as energy for methanol raw material. Burning the Salix is estimated to generate this energy in a cogeneration electricity plant at an average efficiency of 60 %, which gives the new energy demand of 0.095/0.60 = 0.16 MJ_{Salix}/MJ_{RME}. The extra energy need for the cultivation, harvesting and transport of Salix will thus be 0.065x0.16 = 0.01 MJ/MJ_{RME}.

The energy usage for the whole fuel chain for RME and for the two process fuel cases studied is summed up in the following Table 3.6.2 and is illustrated in Figure 3.14 and 3.15.

Table 3.6.2 Energy usage in the vegetable oil (RME) fuel chain

Step		Energy use, MJ/MJ_{RME}	
	Process fuel:	Fossil	Salix
Farming, harvesting		0.30	0.31
Transport		0.02	0.02
Pressing and extraction*		0.06	(0.06)
Refining		0.04	(0.04)
Transesterification		0.02	(0.02)
Methanol for transesterification		0.02	0.02
End distribution		0.01	0.01
	SUM	0.47	0.36
By-product credit		- 0.02	-0.02
	NET SUM	0.45	0.34

( ) renewable energy, not included in sum
* conversion loss not accounted

At vehicle use, refined rapeseed oil (and vegetable oil in general) that has been transformed to a methylester has many characteristics close to those of diesel oil, for instance viscosity, density, energy content, and cetane number. The combustion process in real engine operation is similar for both fuels and it is therefore natural that RME is used in a diesel engine process /70/. A special diesel engine design, called the

Elsbett engine, has often been used in testing of vegetable oils. It has no water cooling system and obtains an improved efficiency through lower heat losses. Some of the unavoidable heat losses are used for preheating of the fuel.

Tests carried out with rapeseed oil are often based on special arrangements which are insufficiently reported. Hence not many tests are comparable to normal test procedures.

It seems, though, as if energy consumption and engine performance are similar to operation with diesel oil /70/. Thus the compilation of the total resource use for RME fuelled vehicles, in Table 3.6.3 below, is based on the diesel oil energy consumption for the catalyst equipped medium heavy duty trucks (10.3 MJ/vkm) and urban buses (16.6 MJ/vkm) of section 3.1. The passenger cars are excluded since there is no widespread usage of diesel engines in passengers cars in Sweden.

Tractors are a group of vehicles that have often been involved in tests with rapeseed oil based fuels. Since this is a fairly small, although not negligible, group of vehicles, for which emission tests are very scarce, it is not considered here.

Table 3.6.3 Total resource use for two vehicles powered by dedicated vegetable oil (RME) fueled diesel engines

RME process fuel:	**Fossil**		**Biomass**	
Resource use (MJ/vkm):	**Total**	**Fossil**	**Total**	**Fossil**
MDT	**14.9**	**4.6**	**15.0**	**3.5**
Bus	**24.1**	**7.5**	**24.2**	**5.6**

3.7 Hydrogen

Hydrogen is in many aspects a theoretically interesting alternative motor fuel. For example, it is fairly easily available (although it costs energy to produce it) and it has a high energy content (LHV), which can be releasee in a fairly clean combustion process. This combustion can even take place at fairly low temperature, in a fuel cell, and results directly in electric energy.

Among the many ways to produce hydrogen, stripping it from hydrocarbons is the least expensive large scale process, while the electrolysis of water is the most common source of hydrogen today in industrial plants. Many plans have been launched lately aiming at utilizing the abundance of solar energy in some parts of the world to produce hydrogen via photoelectrolysis /93/.

Once produced, there are some problems to store the voluminous hydrogen gas in a practical way. There are many possibilities, and some could even become practically useful. Today, when using larger quantities of hydrogen at places where it is not produced, liquid hydrogen (LH) and methyl cyclo-hexan (MCH) seem to be the most reasonable forms in which to handle the hydrogen. In this study only those two forms are considered from a basic energy point of view.

It is assumed, for one case, that the hydrogen is produced in a region where for some reason hydropower is abundant and no better use can be found for it. This might be in a developing region where huge hydropower resources are developed to power stations and possibly a distribution grid, but electricity utilization does not yet compare with its supply. For another case, natural gas is assumed to be the base for power production with the sole or at least the major purpose of producing hydrogen.

Hydrogen is produced by electrolysis of water at or near to the power station, and is transformed there to either of the two aforenamed forms. The hydrogen forms are then transported to the region where they used and distributed. The basic energy data for the steps in the fuel chain are taken from /90/.

Electrolysis requires 1.77 MJ_{el}/MJ_{LH}. Produced in a hydropower plant with surplus of electricity assuming 95% efficiency, this utilizes 1.86 MJ_{ren}/MJ_{LH}. In a natural gas powered combined cycle condensing plant the primary energy demand is 3.73 MJ_{NG}/MJ_{LH}, using the 2.11 MJ_{NG}/MJ_{el} from section 2.1.2. (This is done considering the internal use of electricity in this special plant to be so high that it covers also the distribution loss in a medium sized grid included in the figure of 2.11 above.) For the MCH case, the energy requirement for electrolysis is 1.41 MJ_{el}/MJ_{MCH}.

The liquefaction of hydrogen requires 0.43 MJ_{el}/MJ_{LH}, while the MCH synthesis demands 0.028 MJ_{el}/MJ_{MCH}. This demand of electricity is converted to primary energy in a similar way as above.

For the sea transport, the energy demand is estimated at 0.06 MJ_{fuel}/MJ_{LH} and 0.07 MJ_{fuel}/MJ_{MCH} respectively.

The distribution is estimated to demand, to a large part in form of boil-off losses, 0.11 MJ_{fuel}/MJ_{LH}. The decomposition of MCH, which actually takes place in the vehicle, requires 0.25 MJ_{fuel}/MJ_{MCH}. It is accounted for in parallel with the distribution of MCH and the energy for the latter is neglected in comparison.

The energy usage in the chain for hydrogen up to the hydrogen for use in the vehicle energy converter is compiled in Table 3.7.1 below.

Table 3.7.1 Energy usage in the fuel chain water to hydrogen

Step	Energy use, $MJ/MJ_{hydrogen}$ Hydrogen form: LH-case Electricity gen: hydro	LH-case NG cond.	MCH-case hydro	MCH-case NG cond.
Electrolysis	(1.86)	3.73	(1.48)	2.98
Liquefaction/ MCH-synthesis	(0.45)	0.91	(0.03)	0.06
Sea transport	0.06	0.06	0.07	0.07
Distribution/ MCH-decomp.	0.11	0.11	0.25	0.25
SUM	0.17	4.81	0.32	3.36

( ) renewable energy, not included in sum

For the <u>end use</u> of hydrogen in vehicles only LH in cryogenic tank is considered here. The weight penalty is about 2% for the tank installation for a given driving range. There is a considerable volume penalty (about four times), which is disregarded from an energy view at vehicle use. The thermal efficiency in the engine is, at the use water injection for the lowering of emissions, considered to be 15% more than for gasoline, which is in the lower range of estimates and experience. Only use in passenger cars is considered and the energy consumption is then 2.9 MJ_{LH}/ vkm. This choice is made because the relevant documentation seems to be easily available from the operation of passenger cars and, furthermore, the production of the hydrogen fuel is obviously extremely energy demanding. It seem to be a general understanding that hydrogen is of interest mainly in a post-fossil future where energy is an abundant commodity based on renewable sources /89/.

Total resource use for the passenger car is then as shown in Table 3.7.2 and in Figure 3.16-17.

Table 3.7.2 Total resource use for passenger cars (PC) fueled by hydrogen (LH) from electrolysis of water

Electricity from: Resource use (MJ/vkm):	Hydropower Total	Hydropower Fossil	Natural Gas Total	Natural Gas Fossil
PC	10.1	0.49	16.8	16.8

3.8 Electricity

For charging traction batteries in electric vehicles, the two supply alternatives of section 2.1.2, viz. the national Swedish generation set up and new combined cycle condensing plants fueled by natural gas, are considered.

The national Swedish power generation set up is considered, at an average over a period of normal winters, to require, distribution losses included, an input of 0.14 MJ_{fossil}/MJ_{el} at the outlet point in the electricity distribution grid. The remaining input to get the electricity is here considered to be "renewable". The conversion to electricity is estimated at an efficiency of 95 % and the distribution loss in the national grid is about 7.5 % due to the long transmission distances. Thus for the 95 % of the average Swedish MJ_{el} at an outlet point in the grid about, 1.08 $MJ_{renewable}$ has to be utilized.

The natural gas based power requires 2.11 MJ_{NG}/MJ_{el} at the net outlet point as explained in section 2.1.2.

The charging equipment, that is the charger of the traction battery, is estimated to operate at an efficiency of 0.85, while the battery charging efficiency is considered to be 0.8, which is an average for the traction batteries of possible use today.

Table 3.8.1 Energy usage in the energy chain primary energy to traction battery electricity

	Energy use, $MJ/MJ_{batt.el}$	
Electricity from: **Step**	**Swedish average gen.**	**Natural gas**
Power generation	**0.12** **(0.12)**	**1.55**
Distribution	**0.01** **(0.07)**	**0.08**
Charging to battery	**0.02** **(0.45)**	**0.47**
SUM	**0.15**	**2.10**

( ) renewable energy, not included in sum

The efficiency at the conversion of battery electricity to transport work is about 0.85 in total (electric motor 0.9 and drive train 0.95). The total energy use in the full chain including end use is illustrated in Figure 3.18 and 3.19.

For the end use in vehicles a reasonable energy use is about 0.4 MJ_{el}/tonkm from the battery. For the three model vehicles of section 2.4 this mode of propulsion implies a weight penalty if the maximum payload capacity is to be kept. With or without maximum payload capacity kept, performance of the EVs is not fully comparable to the conventionally powered vehicles. Still, with lower top performance the EVs could do a decent job in urban traffic, and the total resource use in energy terms is compiled and shown in Table 3.8.2 below.

In this compilation it is assumed that the total estimated battery weight (400 kg for PC, 2 000 kg for MDT and 3 000 kg for Bus) is added as a weight penalty for each model vehicle, which thus incurs a larger energy consumption. This is a simple way, not obviously underestimating the effect, to compensate for the expected larger operating weight of EVs.

Table 3.8.2 Total resource use for three vehicles fueled by battery electricity

Electricity from:	**Swedish average gen.**		**Natural Gas**
Resource use (MJ/vkm):	**Total**	**Fossil**	**Fossil only**
PC (+30% op.w.)	**1.2**	**0.14**	**2.1**
MDT (+20%)	**8.6**	**0.96**	**14.9**
Bus (+25%)	**10.9**	**1.22**	**18.8**

In the above treatment the difference in specific fuel consumption between the model vehicles has been taken care of in a schematic and simplified way. It could be of interest to study the possible use of electricity, for instance in the MDT, in somewhat more detail. Experience from the Stockholm battery bus project /106/ indicate that the actual electricity demand for bus propulsion is in line with the above figures, even though the cost for the batteries per vkm was a deterrent.

For electric hybrid vehicles the energy supply does not necessarily have to involve the electricity distribution grid or any other electricity source outside the vehicle. Depending on the engine type used in a possible motor/generator device and the fuel chosen for this, or for a fuel cell for traction, the energy resource use for the full hybrid chain varies. Hybrid vehicles may become an alternative of some interest already in the 1990s but is not included in this study, since the number of alternatives studied had to be included. Many features of some hybrid vehicles can, however, be picked out of this report. For other hybrid alternatives, e g a series hybrid with a motor/generator device, complementary studies on efficiencies and operating strategy for a specific design have to be done in order to get a reasonably fair comparison. Following the battery bus project /106/ the Stockholm local traffic authority went on with a prototype hybrid bus project, using a passenger car otto engine equipped with a three-way catalyst in a motor/generator device. This project is not reported yet but indications of a minor group of some more hybrid buses of this type to follow, are there.

URBAN DIESEL OIL

(0.001 weight % sulfur)

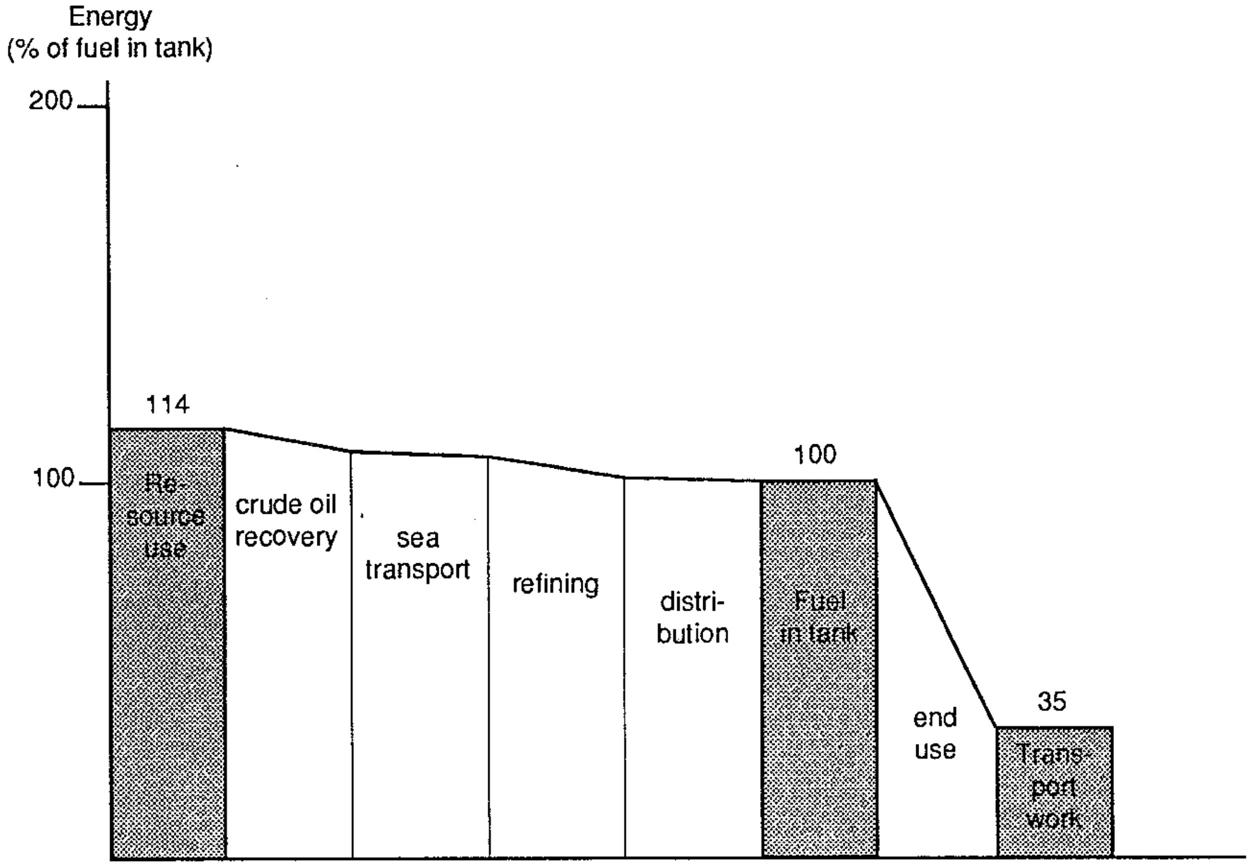

Figure 3.1 Energy turnover in the fuel chain crude oil recovery to urban diesel oil use in heavy duty diesel engine operated in bus cycle.

▨ Shaded box = state of fossil energy

⬚ Shaded box = state of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

GASOLINE

(REFORMULATED)
(0.010 weight % sulfur)

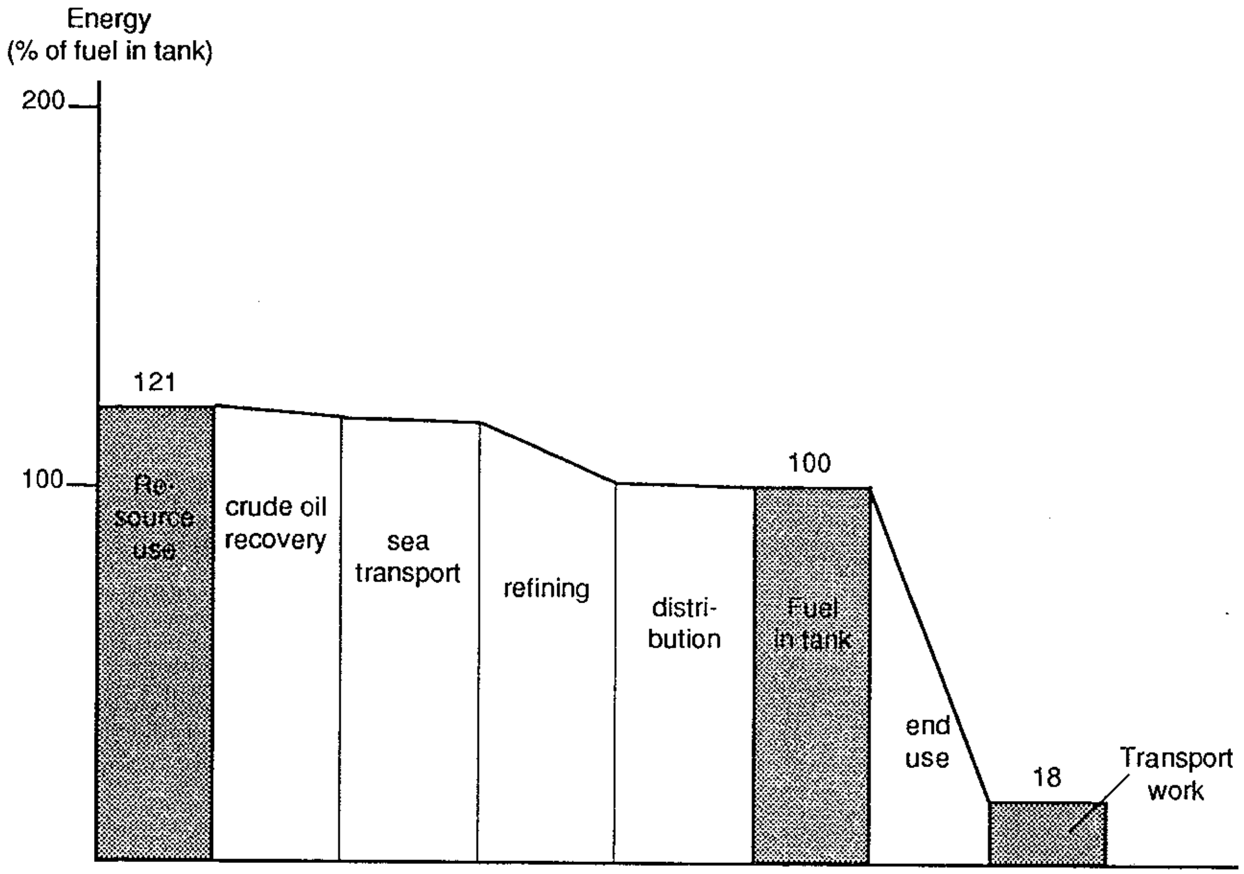

Figure 3.2 Energy turnover in the fuel chain crude oil recovery to reformulated gasoline use in light duty otto engine operated in FTP-cycle.

▩ Shaded box = state of fossil energy

⬚ Shaded box = state of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

PROPANE

(REFINERY)

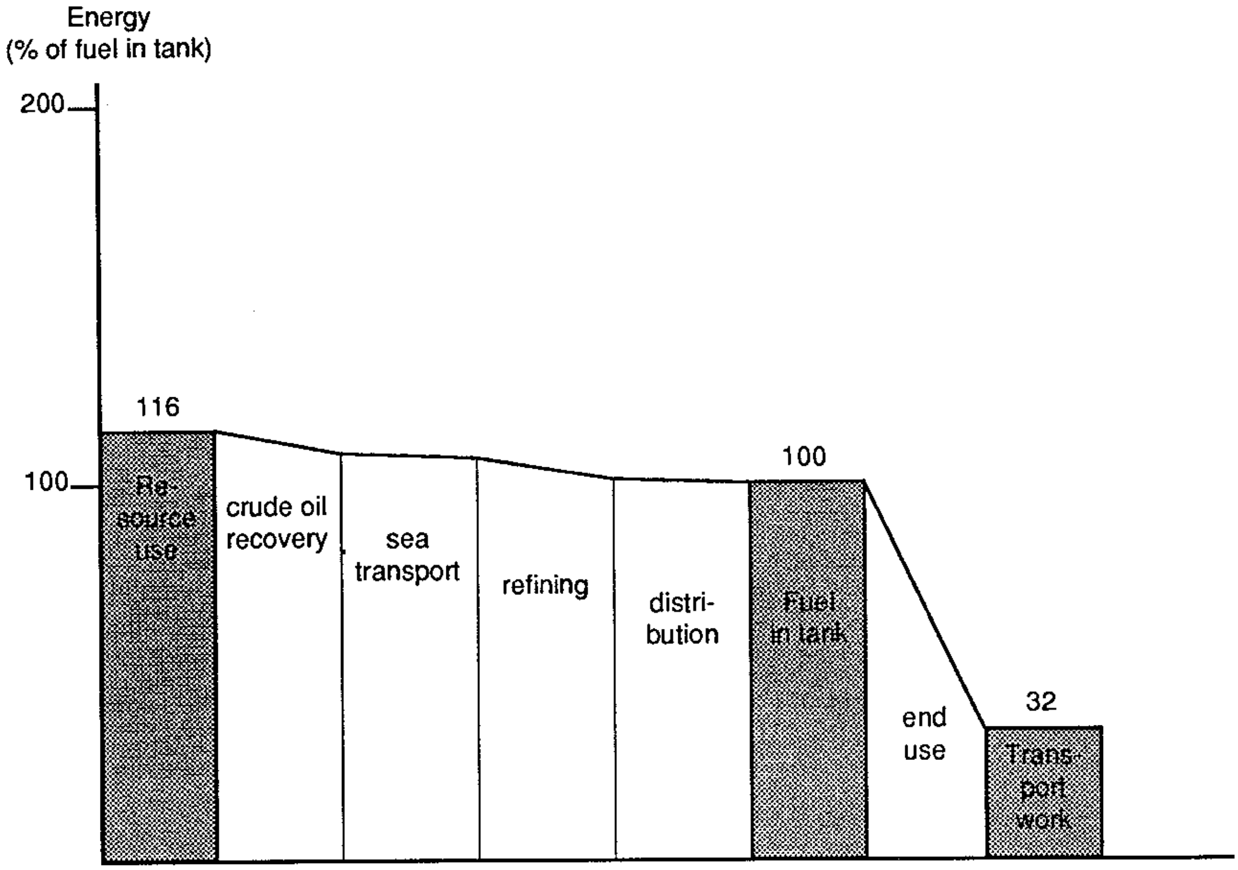

Figure 3.3 Energy turnover in the fuel chain crude oil recovery to propane use in heavy duty otto engine operated in bus cycle.

▨ Shaded box = state of fossil energy

⬚ Shaded box = state of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

NATURAL GAS

COMPRESSED NATURAL GAS, CNG

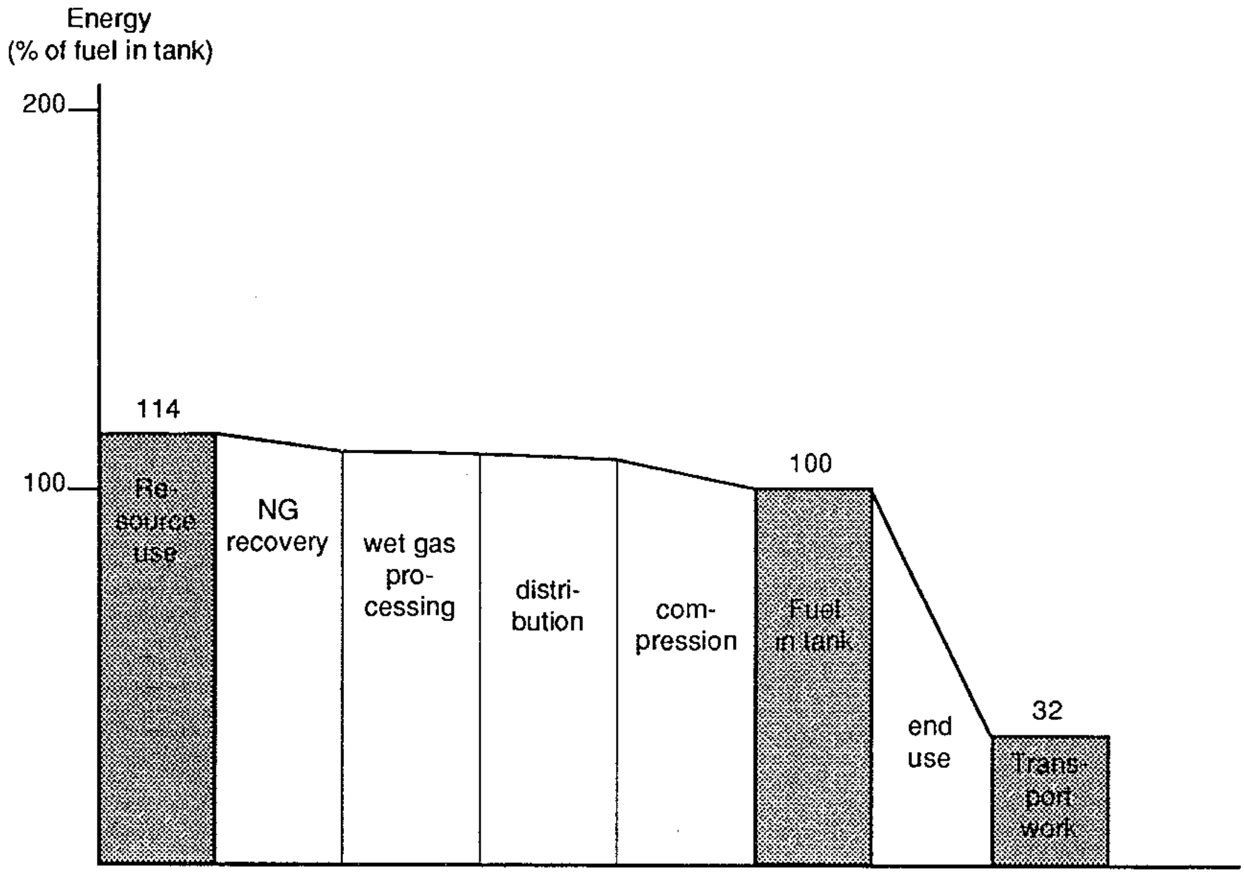

Figure 3.4 Energy turnover in the fuel chain natural gas recovery to CNG use in heavy duty otto engine operated in bus cycle.

▨ Shaded box = state of fossil energy

⬚ Shaded box = state of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

BIOGAS

(FOSSIL PROCESS FUEL CASE)

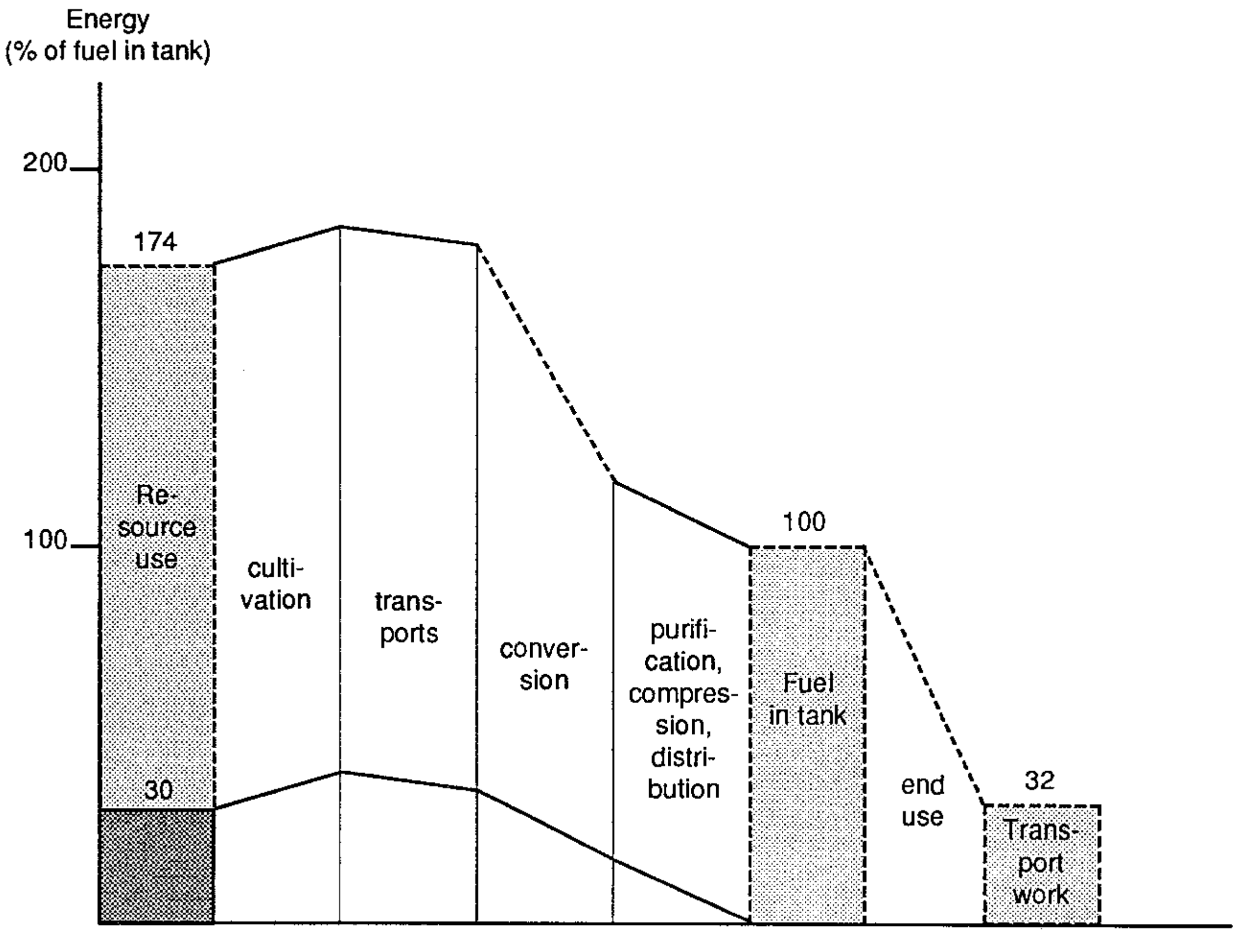

Figure 3.5 Energy turnover in the fuel chain lucerne growing to compressed methane use in heavy duty otto engine operated in bus cycle.

▩ Shaded box = state of fossil energy

▨ Shaded box = state of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

BIOGAS

(BIOGAS PROCESS FUEL CASE)

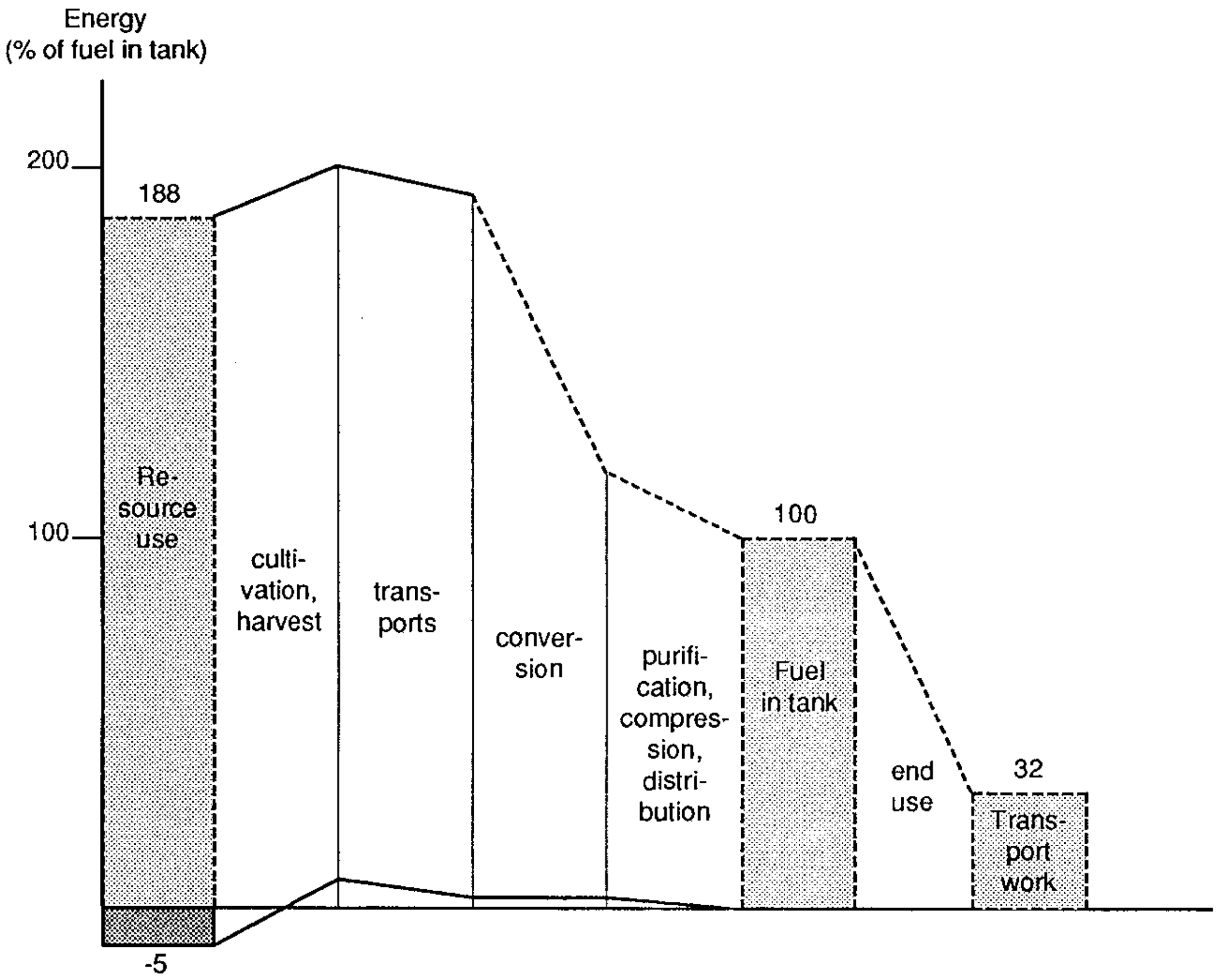

Figure 3.6 Energy turnover in the fuel chain lucerne growing to compressed methane use in heavy duty otto engine operated in bus cycle.

▨ Shaded box = state of fossil energy

⬚ Shaded box = state of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

METHANOL

(NATURAL GAS BASED)

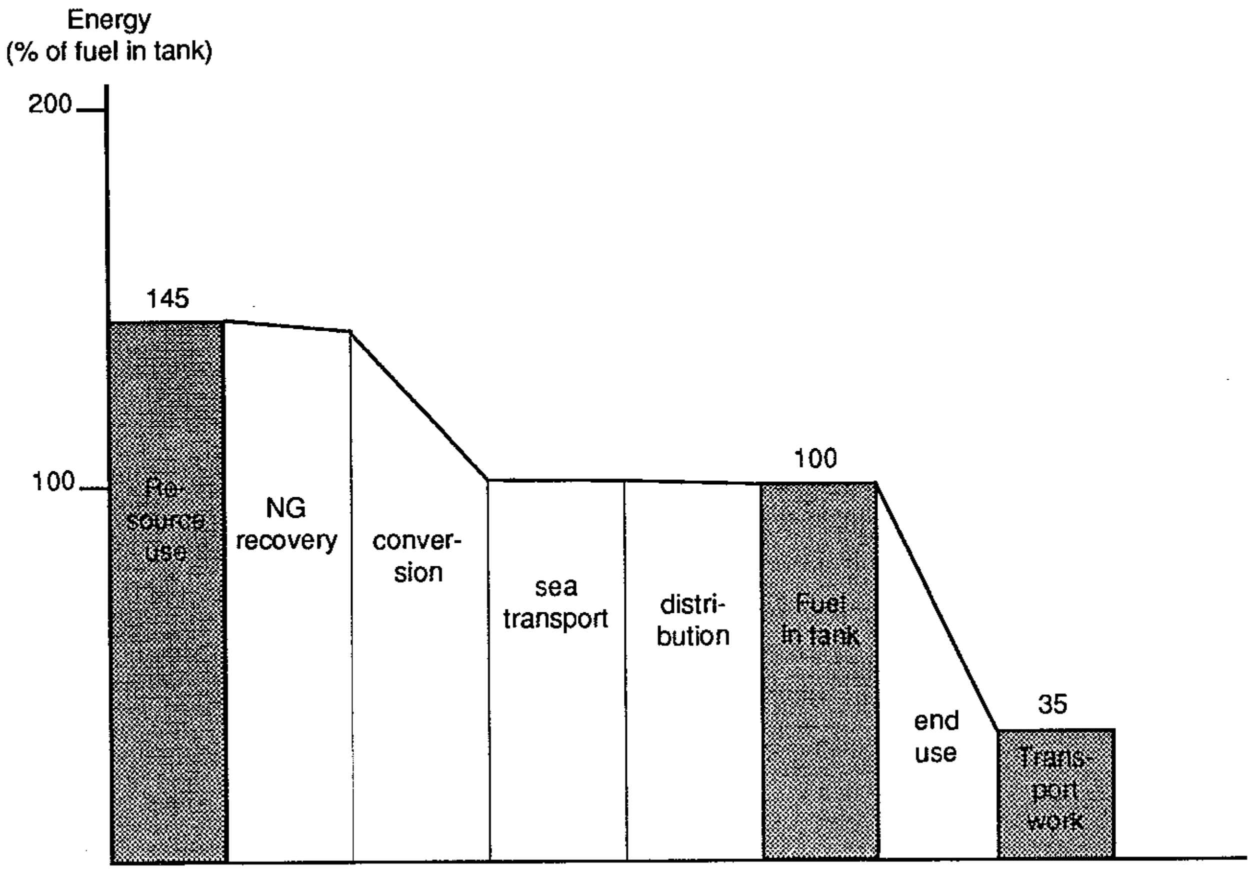

Figure 3.7 Energy turnover in the fuel chain natural gas recovery to methanol use in heavy duty diesel engine operated in bus cycle.

▨ Shaded box = state of fossil energy

⬚ Shaded box = state of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

METHANOL

(SALIX BIOMASS)

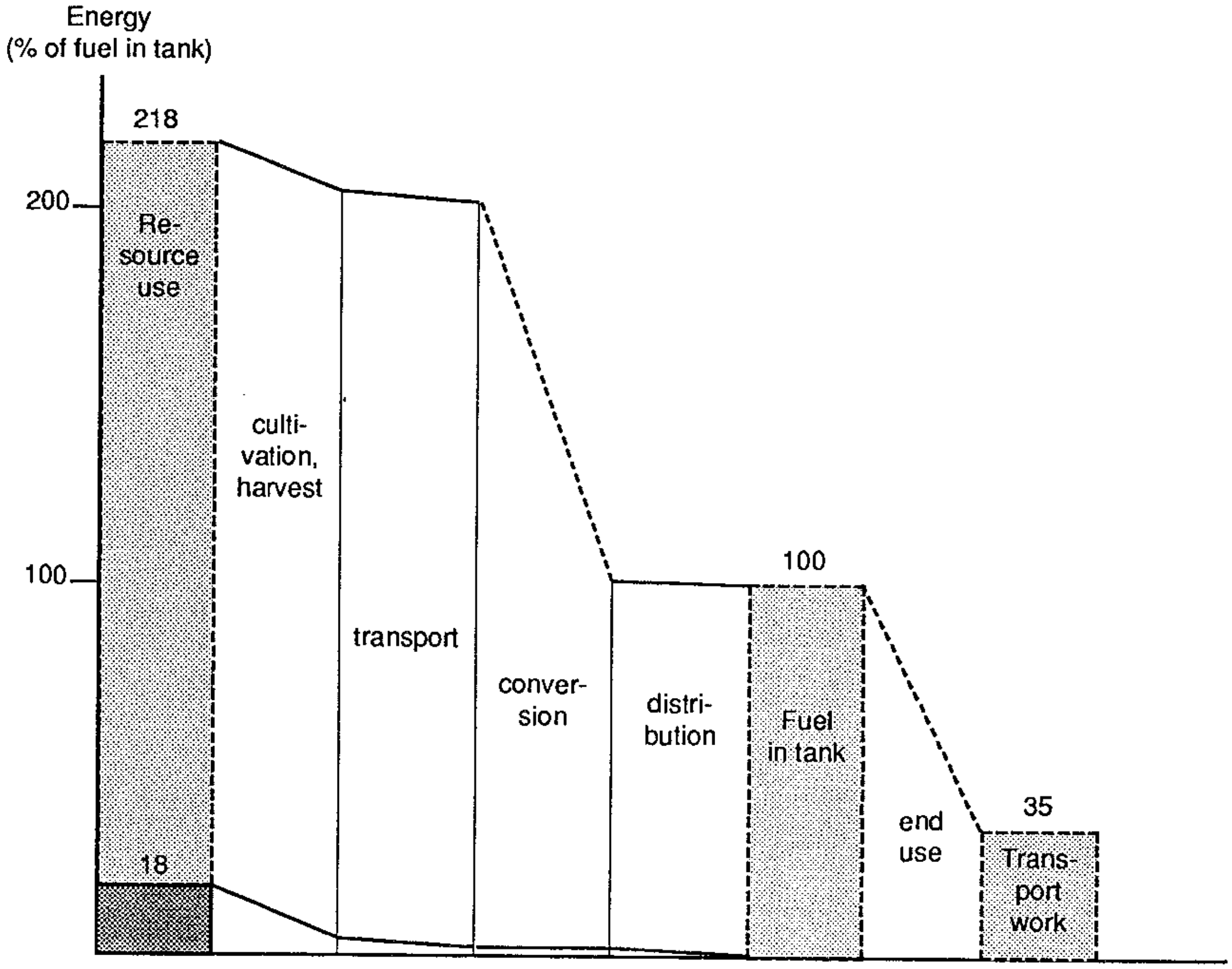

Figure 3.8 Energy turnover in the fuel chain Salix growing to methanol use in heavy duty diesel engine operated in bus cycle.

▨ Shaded box = state of fossil energy

⬚ Shaded box = state of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

METHANOL

(TREE RESIDUES)

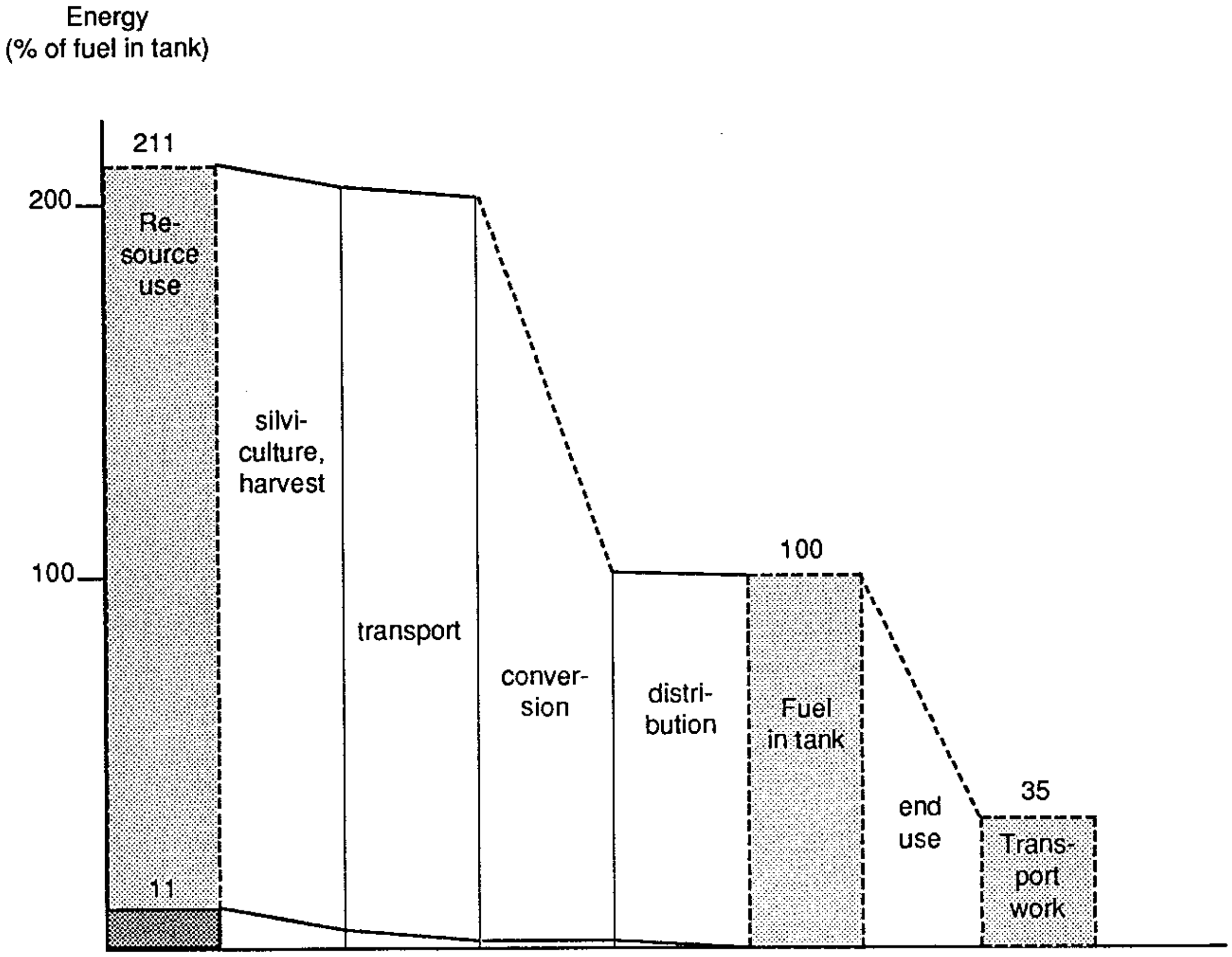

Figure 3.9 Energy turnover in the fuel chain tree residues to methanol use in heavy duty diesel engine operated in bus cycle.

▨ Shaded box = state of fossil energy

⬚ Shaded box = state of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

ETHANOL

(WHEAT/FOSSIL PROCESS FUEL)

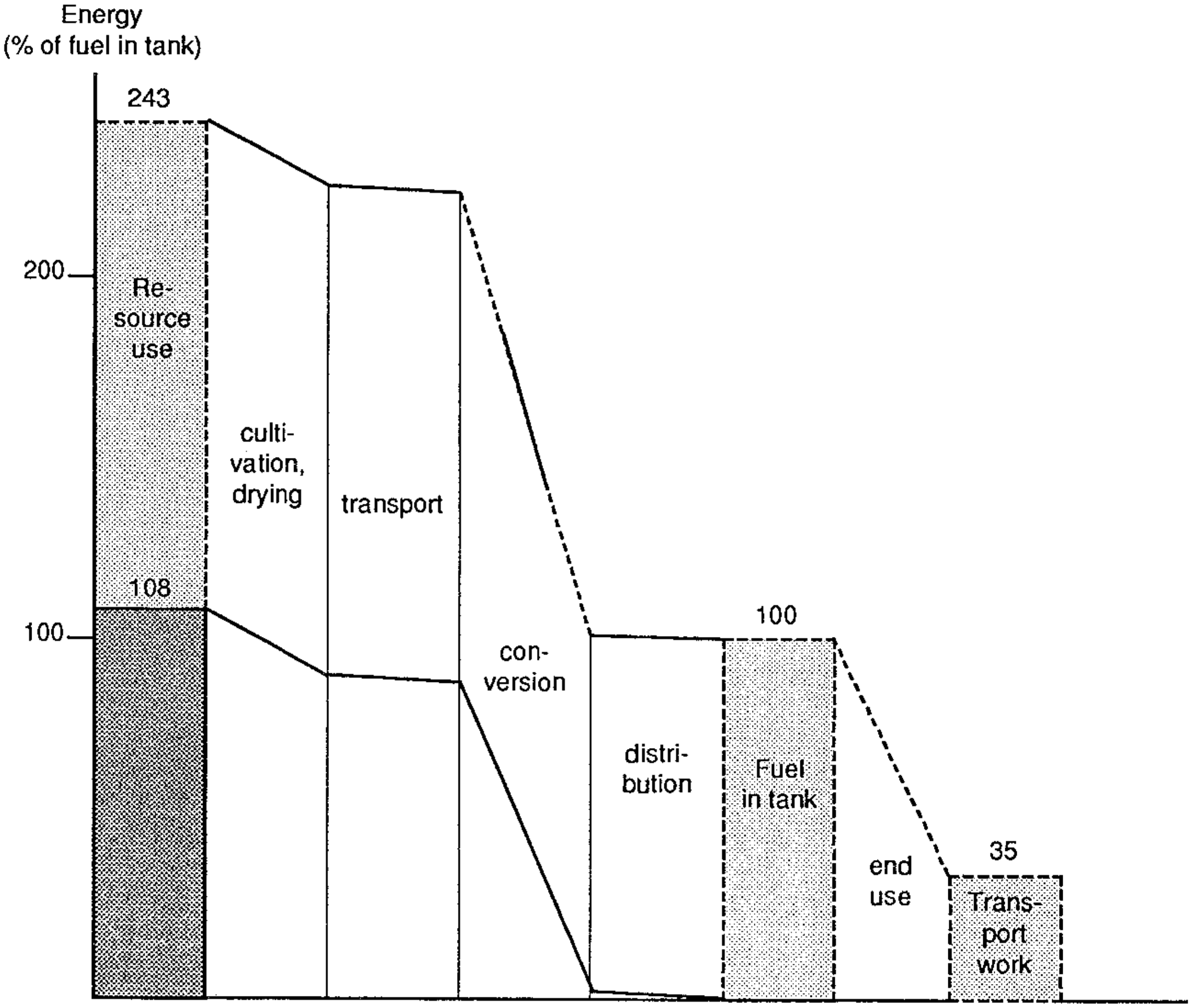

Figure 3.10 Energy turnover in the fuel chain wheat growing to ethanol use in heavy duty diesel engine operated in bus cycle.

▨ Shaded box = state of fossil energy

⬚ Shaded box = state of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

ETHANOL

(WHEAT/STRAW CASE)

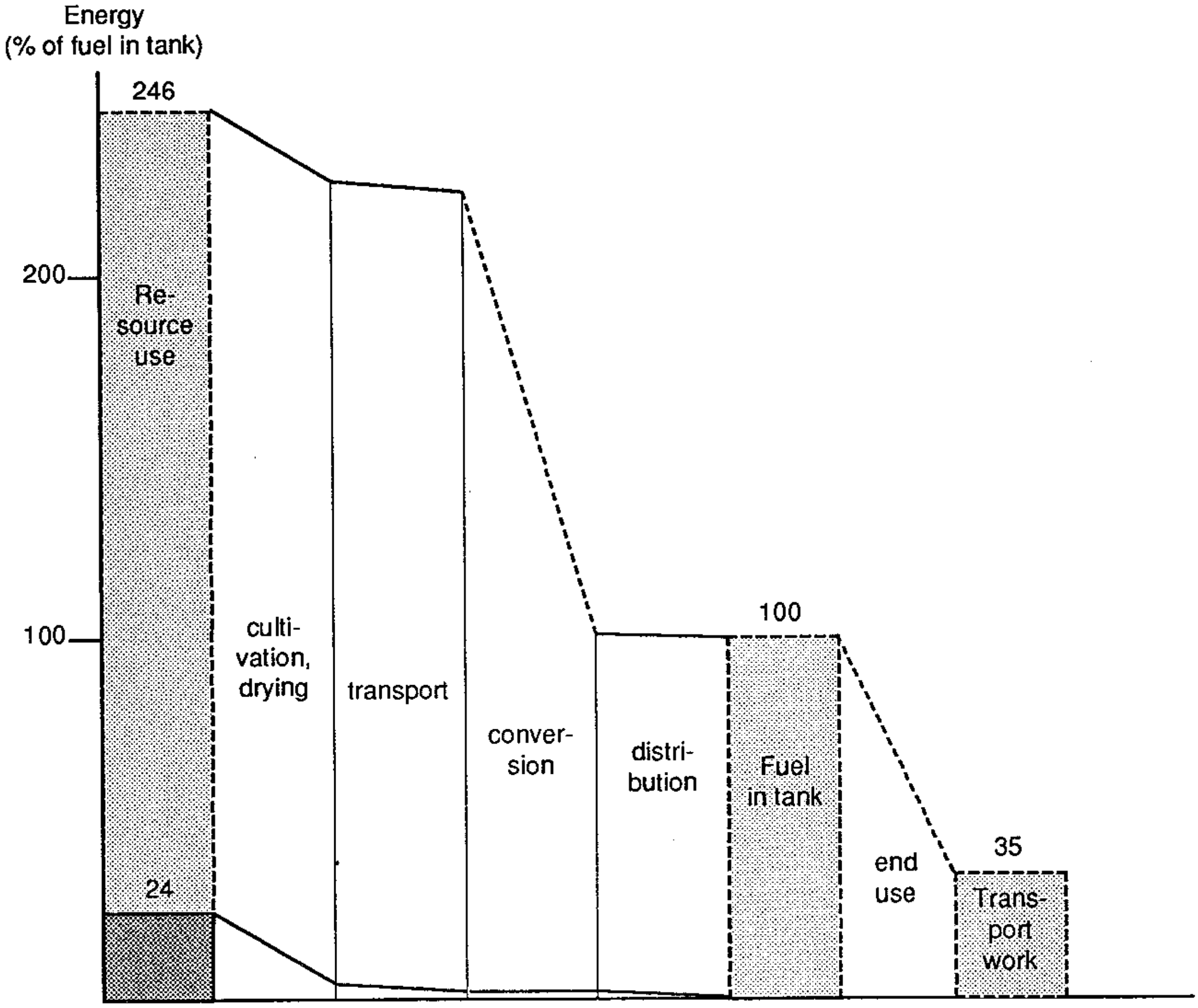

Figure 3.11 Energy turnover in the fuel chain wheat growing to ethanol use in heavy duty diesel engine operated in bus cycle.

▨ Shaded box = state of fossil energy

⬚ Shaded box = state of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

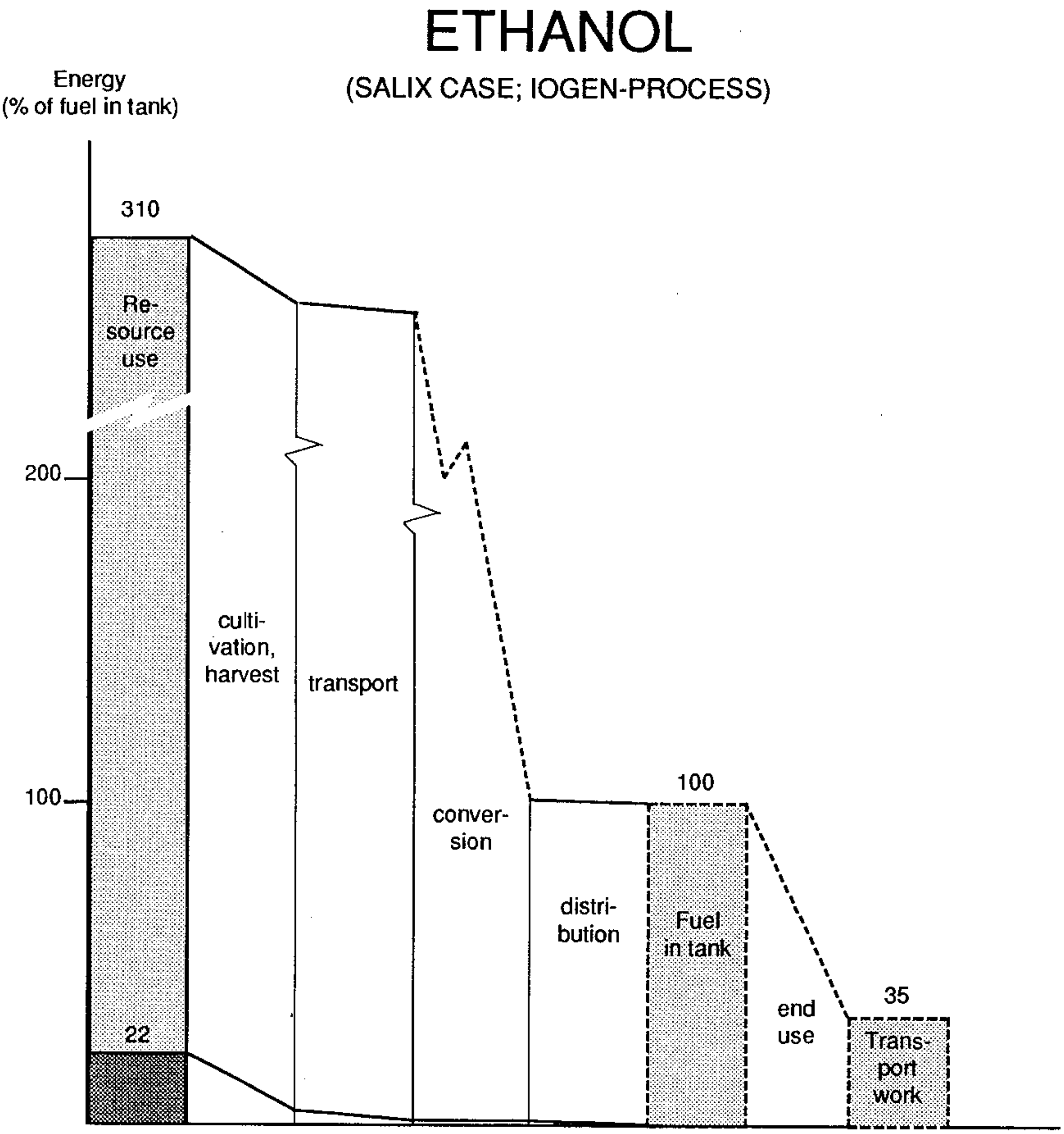

Figure 3.12 Energy turnover in the fuel chain Salix growing to ethanol use in heavy duty diesel engine operated in bus cycle.

▨ Shaded box = state of fossil energy

⬚ Shaded box = state of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

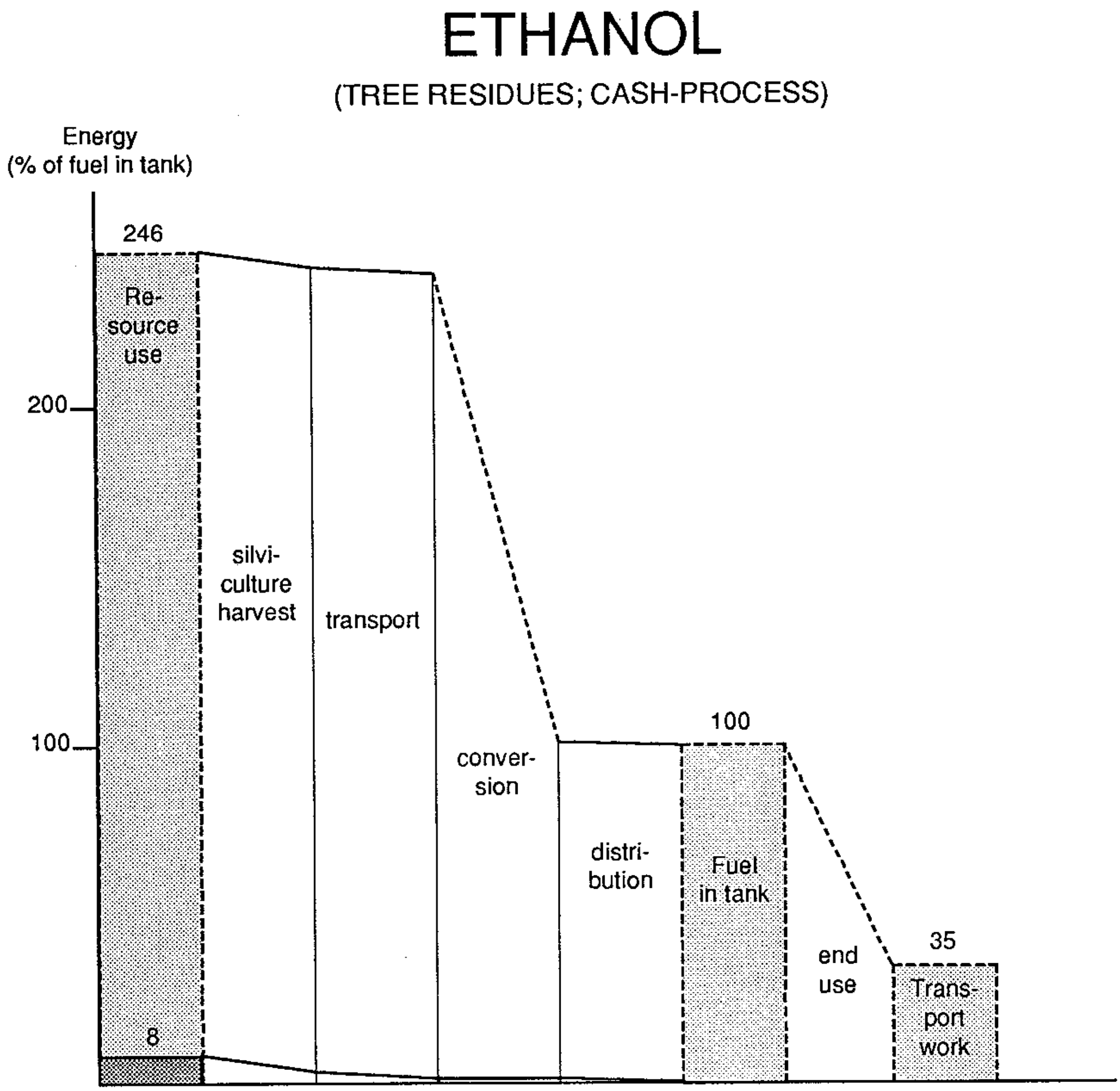

Figure 3.13 Energy turnover in the fuel chain tree residues to ethanol use in heavy duty diesel engine operated in bus cycle.

▨ Shaded box = state of fossil energy

⬚ Shaded box = state of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

RME

RAPESEED OIL METHYL ESTER
(FOSSIL PROCESS FUEL CASE)

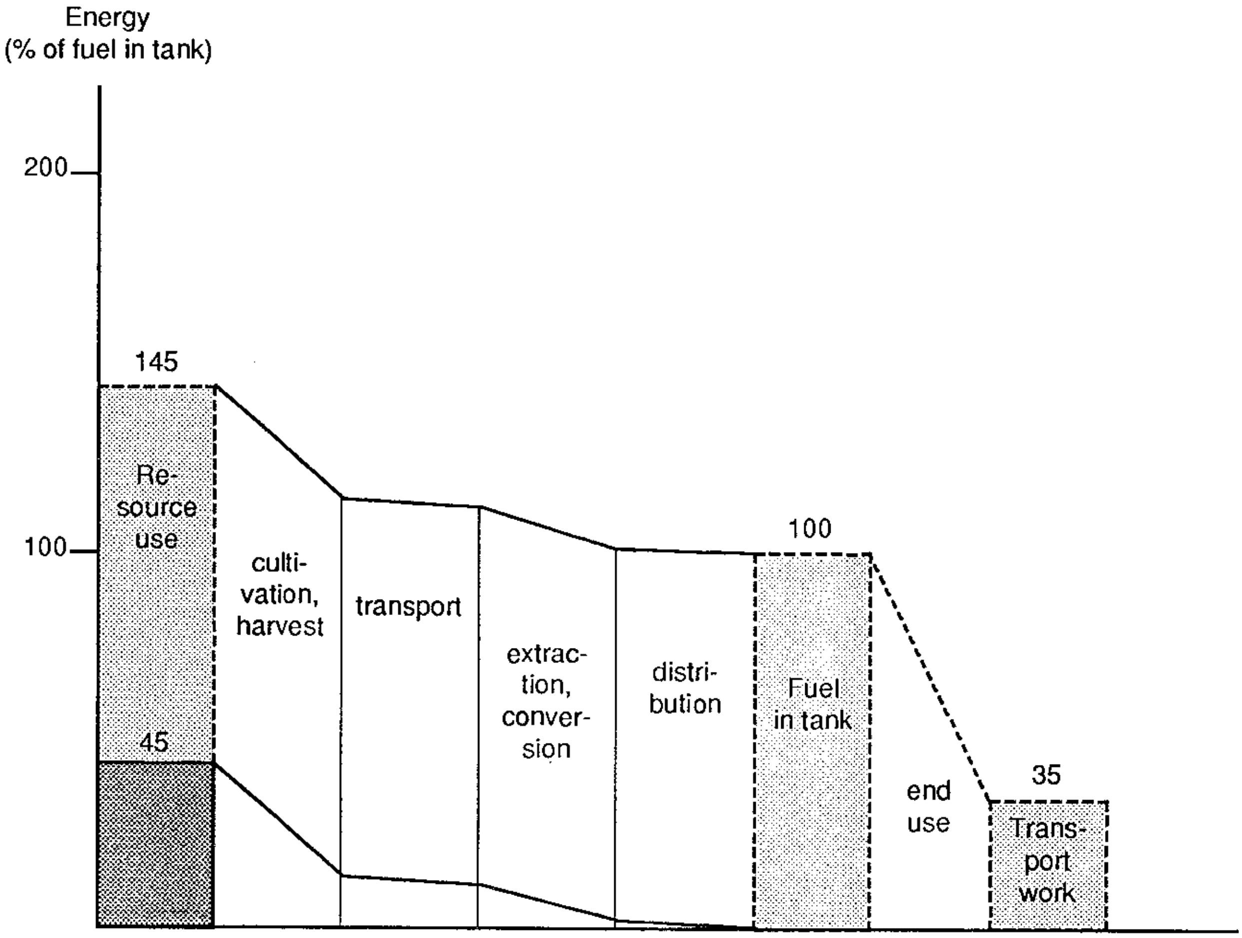

Figure 3.14 Energy turnover in the fuel chain rape growing to RME use in heavy duty diesel engine operated in bus cycle.

▨ Shaded box = state of fossil energy

⬚ Shaded box = state of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

RME

RAPESEED OIL METHYL ESTER
(BIOGAS PROCESS FUEL CASE)

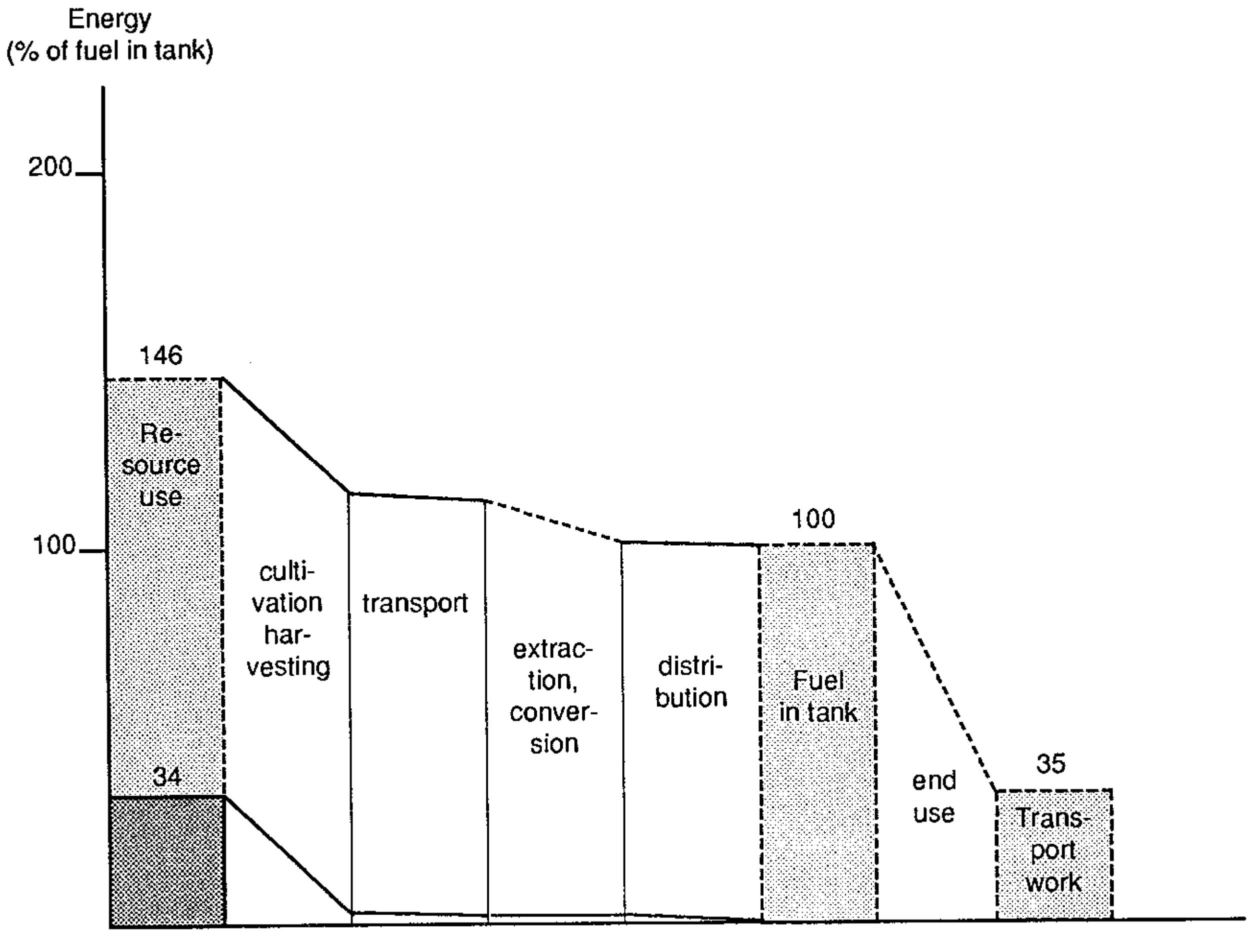

Figure 3.15 Energy turnover in the fuel chain rape growing to RME use in heavy duty diesel engine operated in bus cycle

▩ Shaded box = state of fossil energy

⬚ Shaded box = state of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

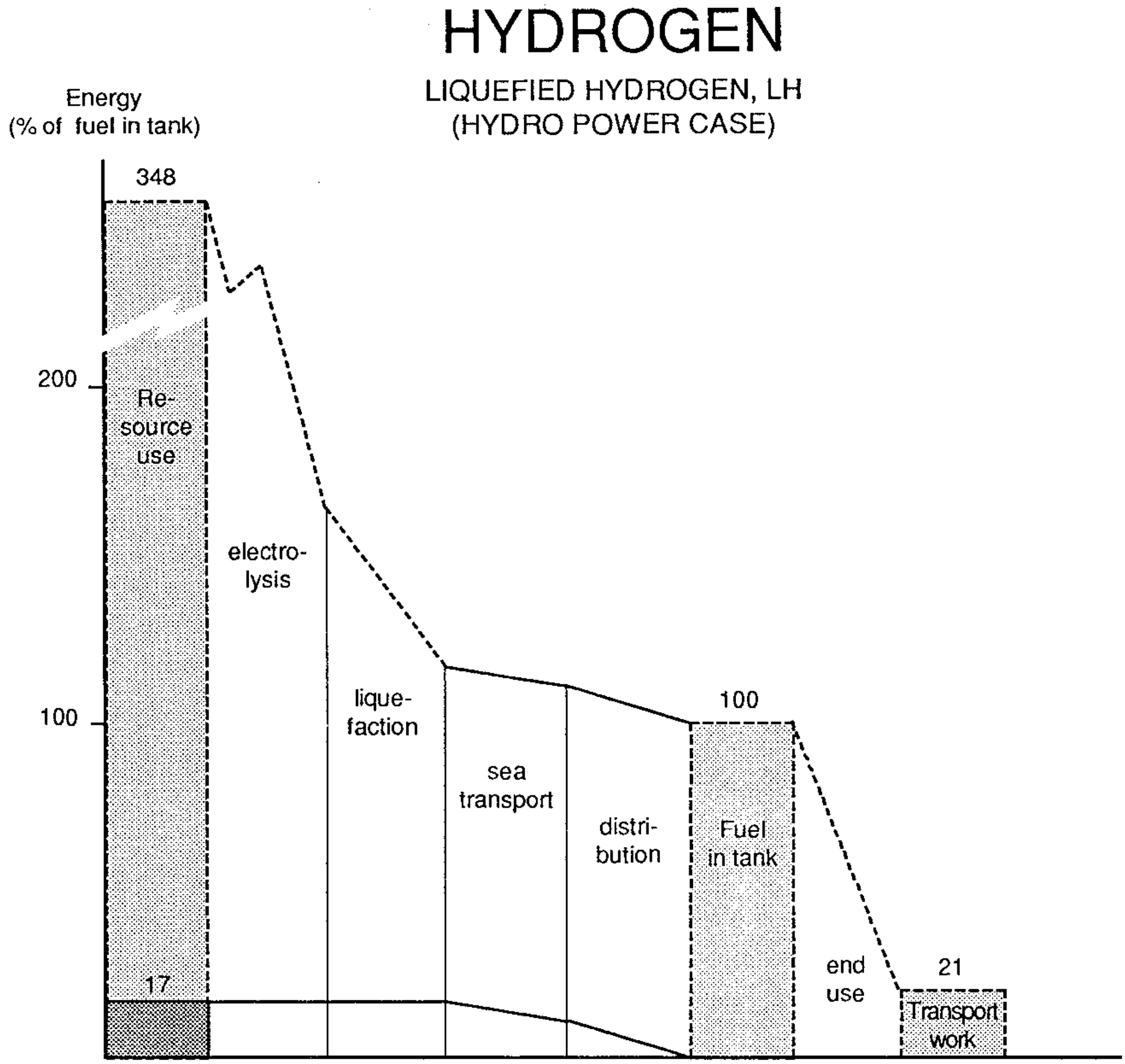

Figure 3.16 Energy turnover in the fuel chain water to hydrogen (LH) use in light duty otto engine.

▨ Shaded box = State of fossil energy

▨ Shaded box = State of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

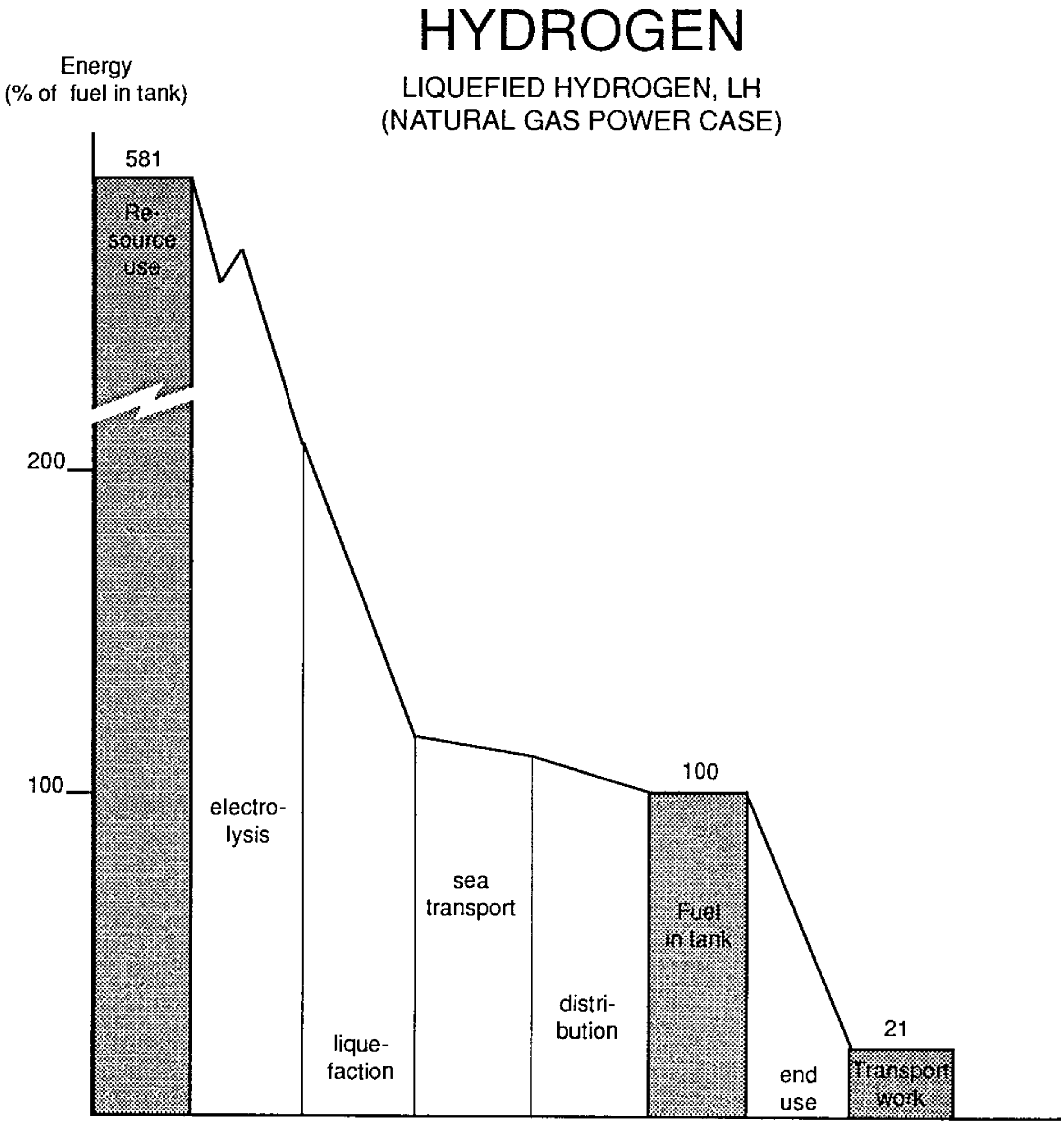

Figure 3.17 Energy turnover in the fuel chain water to hydrogen (LH) use in light duty otto engine.

▨ Shaded box = State of fossil energy

⬚ Shaded box = State of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

ELECTRICITY

(SWEDISH AVERAGE GENERATION)

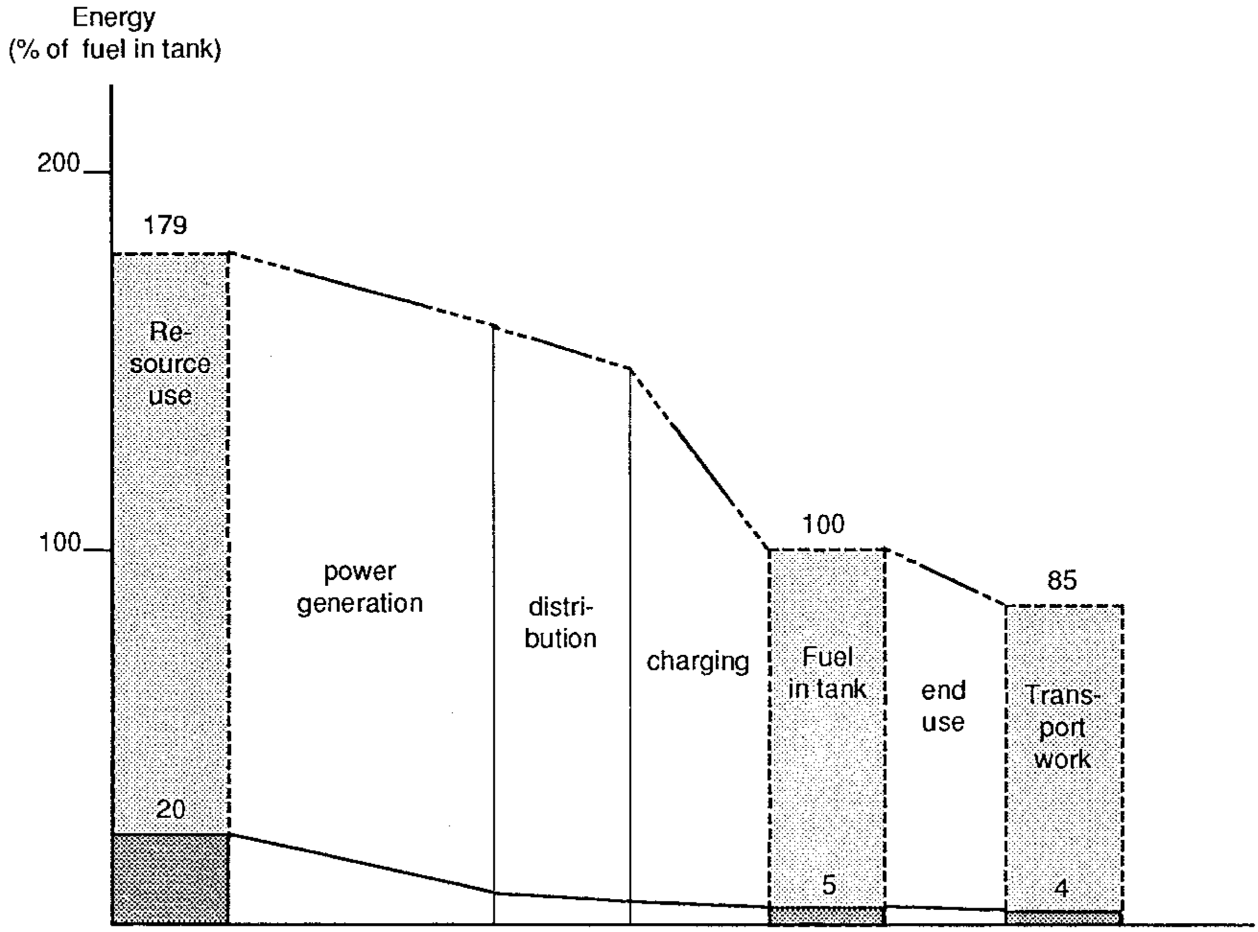

Figure 3.18 Energy turnover in the fuel chain primary energy to electricity use in electric motor.

▩ Shaded box = State of fossil energy

⬚ Shaded box = State of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

ELECTRICITY

(NATURAL GAS)

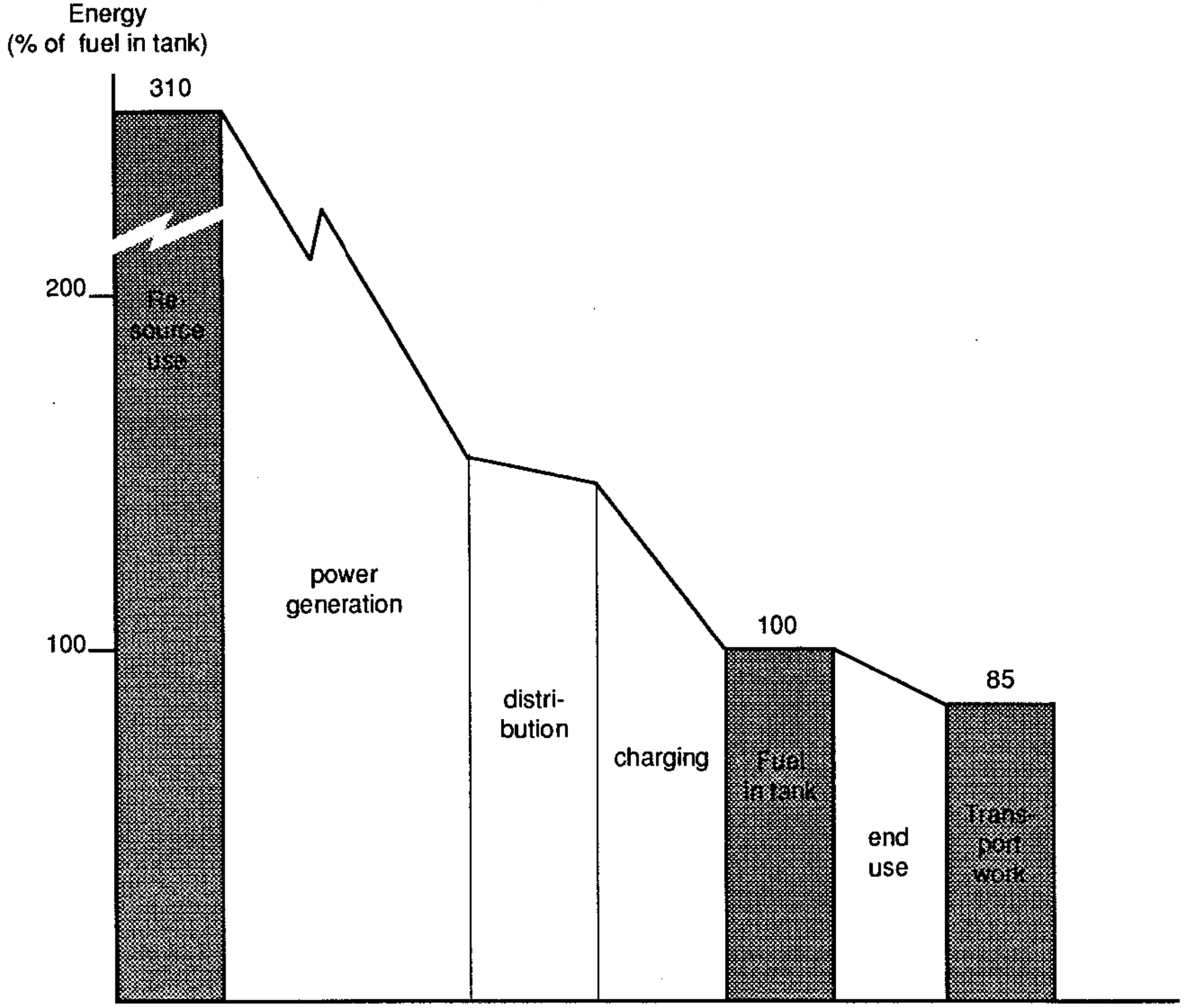

Figure 3.19 Energy turnover in the fuel chain primary energy to electricity use in electric motor.

▨ Shaded box = State of fossil energy

⬚ Shaded box = State of renewable energy

—— Solid line = alteration of fossil energy use

----- Dashed line = alteration of renewable energy use

4. EMISSIONS

Emissions in the different stages of the fuel chain will be calculated on the basis of the usage, type of fuel and typical emissions of each stage. Complete data are not available.

4.1 Diesel oil, gasoline

There are not yet any measurements available from transient tests on chassis dynamometer with the new urban diesel oils in catalyst equipped vehicles. Results from engine dynamometer testing /76/ indicate some reductions (5-25 %) of all types of emissions, which may be further enhanced by optimizing the engine for lower NOx-emissions without increased HC and particle emissions. The oxidation catalyst will reduce CO and HC emissions to much below 1 g/vkm. Measured and projected emissions have been summarized in Table 4.1.1 with bus emissions referred to the German bus cycle.

Table 4.1.1 Present and projected average lifetime emissions

Compound **Category** **fuel**	**CO**	**HC**	**NOx**	**Part.**	**CO_2**	**CH_4**	**N_2O**
	g/vkm					**mg/vkm**	
Car with catalyst gasoline	**7.6**	**0.9***	**0.4**	**0.005**	**256**	**100**	**70**
Ditto reformulated gasoline	**6**	**0.8°**	**0.4**	**0.005**	**256**	**100**	**70**
Urban bus diesel oil	**2.3**	**1.7**	**20**	**1**	**1200**	**100**	**50-600**
Ditto with catalyst urban diesel oil	**0.5**	**0.5**	**14-18**	**0.3**	**1200**	**90**	**50-600**

* +0.05 by evaporation
° +0.04 " "

continued

Compound **Category** **fuel**	**ethene, propene**	**benzene**	**alde-hydes**	**PAC (Σ14)**	**mutagenicity (TA98±S9)**
	mg/vkm			**µg/vkm**	**rev/vm**
Car with catalyst gasoline	**15**	**6**	**7**	**4**	**2**
Ditto reformulated gasoline°	**15**	**2**	**7**	**4**	**2**
Urban bus diesel oil	**100**	**15**	**170**	**200**	**300+**
Ditto with catalyst urban diesel oil°	**25**	**5**	**20**	**50**	**100**

° preliminary projected data

The influence of the urban diesel oils (10 ppmw sulfur, <10 vol% aromatics) on the market today (in Sweden) is most evident on emissions of sulfur oxides and PAC, even without the use of catalysts, because of the low contents of these compounds in the fuel. Tentative, estimated values for emissions in the whole fuel chain with end use as urban diesel oil in buses are given in Table 4.1.2 and for gasoline in passenger cars in Table 4.1.3 (see appendix 4.1 for details). In the tables the total greenhouse gases calculated as CO_2-equivalents have also been included, using the conversion factors given in Table 2.3, section 2.2.3. The data are illustrated in Figures 4.1 - 4.4.

Table 4.1.2 Emissions in the whole fuel chain per MJ motor fuel. Urban diesel oil (10 ppmw sulfur) used in urban bus.

Compound Step (fuel)	CO_2 g/MJ_{fuel}	SOx ---------	NOx	CO mg/MJ_{fuel}	HC	CH_4 ---------	N_2O	ΣCO_2-equiv. g/MJ_{fuel}
Crude recovery (wet NG)	1.8	<1	8	5	2	26	<<1	2.5
Sea transport (bunker C-oil)	0.6	10	20	<1	1	<<1	<<1	1
Refining (gas+HFO+coke)	7	10	6	<<1	10	nd	1.5	≥7.5
Distribution (diesel oil)	1	≈0	10	<1	<1	<<1	<<1	1
End use (urban bus with catalyst, 16.6 MJ_{fuel}/vkm)	72	<1	850-1100	30	30	5	3-35	79--90
							TOTAL	≈96

nd = no data

Table 4.1.3 Emissions in the whole fuel chain per MJ motor fuel. Reformulated gasoline (100 ppmw S) in passenger car.

Compound Step (fuel)	CO_2 g/MJ_{fuel}	SOx --------	NOx	CO mg/MJ_{fuel}	HC	CH_4 ----------	N_2O	ΣCO_2-equiv. g/MJ_{fuel}
Crude recovery (wet NG)	1.8	<1	8	5	2	26	<<1	2.5
Sea transport (bunker C-oil)	0.6	10	20	<1	1	<<1	<<1	1
Refining (gas+HFO+coke)	12	17	10	<<1	17	nd	2	≥13
Distribution* (diesel oil)	1	≈0	10	<1	30	<<1	<<1	1.5
End use (car with catalyst, 3.4 MJ_{fuel}/vkm)	75	5	120	1760	250	30	20	90.5
							TOTAL	≥108

* incl. gasoline evaporation loss

Reformulation of gasoline to obtain less harmful emissions (evaporative and exhaust) have been intensely studied in the U.S. The legislated goals to be achieved were first 15 % and later 25 % reduction of volatile organic precursors to ozone and of air toxics (mainly benzene) and to lower CO emissions to bring air quality values within standards. The joint auto/oil industry studies /103/ are still ongoing and final guidelines on the composition of reformulated gasoline cannot be given. Likely measures to be taken are to reduce total volatility, limit the content of olefines, aromatics (max. 25 vol%) and sulfur, limit the benzene content to max. 1 vol% and use oxygenates (mainly ethers like MTBE) in amounts corresponding to 2-3.5 % by weight of oxygen. The changes must not bring about any increase in emissions of NOx.

Study results have so far confirmed that 5-15 % reduction of CO emissions and 5-6 % of HC emissions could be obtained at no significant change of NOx by reformulations in comparison to industry average gasoline. Older models (1983-85) did not always respond to the changes in the same way as the 1989 models. Air quality modeling studies indicate that peak ozone levels could be reduced up to 26 %. Achievable emission reductions are mode-rate but useful as they can be applied to both existing and near future new cars.

The major effects of the reformulation of gasoline from the emission point of view are the compositional changes of the emissions to atmospherically less reactive components and to less air toxics such as benzene. This effect might be higher in European gasoline due to its higher content of benzene and aromatics.

4.2 Propane (LPG)

Propane-fueled vehicles have sealed storage tanks and no evaporative emissions are assumed. At refueling a small amount is vented to the atmosphere when disconnecting the fill nozzle. This amount is estimated to be 25 mg of propane and is neglected here.

Little analysis of the exhaust emissions potential of propane has been conducted, particularly with the modern systems for lambda-one control and the use of 3-way catalysts, which are probably required to meet future stringent regulations. Although many hundred thousands of LPG-fueled vehicles are on the roads they are all retrofitted gasoline vehicles, often with gasoline operation retained (dual-fuel vehicles). Devices for air/fuel-ratio control are often too inaccurate and are tuned to take advantage of the good lean-burning property of propane, making catalytic NOx-reduction inefficient.

Measured data tend, in comparison to baseline gasoline cars, to be skewed towards reduced emissions of particularly CO (50-80 %), somewhat higher NOx and unchanged total HC emission but with large variations between individual vehicles. Hydrocarbon emissions are, however, less reactive than gasoline engine emissions. Test data easily meet the U.S. federal emission regulations. The potential for low unwanted emissions is probably larger than has hitherto been measured.

Older measurements with cars without catalysts indicated that ethene and propene were present in equal or higher concentrations compared to gasoline operation, but only traces of monoaromatics. Aldehydes (formaldehyde, acetaldehyde, and acrolein) and alcohols were present as in gasoline operation. PACs were at a very low level and no mutagenicity could be measured in the particulates.

Similar earlier measurements with propane-fueled heavy duty engines (converted diesel engines) in buses on chassis dynamometers operating according to the city bus cycle, showed emissions of aldehydes as for diesel oil fueled buses. Some aliphatic aldehydes were detected but no aromatic aldehydes. Mass particle emissions were below 0.1 g/km. Some indications of emissions of semivolatile PACs were obtained and some mutagenicity. The origin might have been crankcase oil entering the combustion chamber.

On this very insufficient data basis and assuming reasonable reductions in the feedback control/3-way catalytic system the following emissions are <u>projected</u> for propane-fueled vehicles (Table 4.2.1). There are as yet only indications from tests with the best systems under development that the figures below can be achieved.

Table 4.2.1 Projected emissions from propane fueled vehicles equipped with 3-way catalysts.

Compound Category	CO_2	CO	HC	NOx	Part.	CH_4	N_2O
	---------	g/vkm	---------			- mg/vkm -	
Car with catalyst	202	1.5	0.6	0.4	-	nd	nd
Urban bus with catalyst	1180	2.5	1	4	<0.1	nd	nd

continued

Compound Category	ethene, propene	benzene	form-, acet- aldehyde	PAC (Σ14)	mutagenicity (TA98±S9)
	--------	mg/vkm	-------	µg/vkm	rev/vm
Car with catalyst	30	0	10 5	2	≈0
Urban bus with catalyst	nd	nd	30 10	?	?

nd = no data ? = inconclusive data

Tentative, estimated emissions in the whole fuel chain from oil and gas recovery to end use of propane in otto engines in cars and buses are given in Table 4.2.2. (See app. 4.2 for details.) In the table also the total greenhouse gases calculated as CO_2-equivalents, using the conversion factors in Table 2.3, section 2.2.3, have been included.

Table 4.2.2 Emissions in the whole fuel chain per MJ motor fuel. Propane.

Compound	CO_2	SOx	NOx	CO	HC	CH_4	N_2O	ΣCO_2-equiv.
Step (fuel)	$g/MJ_{propane}$	------	$mg/MJ_{propane}$	--------				$g/MJ_{propane}$
Crude/NG recovery (wet NG)	1.8	<1	8	5	2	26	<<1	2.5
Wet gas terminal (NG)	1	<1	5	3	1	25	<<1	1.5
Sea trp.(crude) (bunker C-oil)	0.6	10	20	<1	1	<<1	<<1	1
Refining (gas+HFO+coke)	8	11	6	<<1	11	nd	0.3	8
Sea trp.(propane) (bunker C-oil)	1.5	4	42	1	2	<<1	<<1	2
Land distribution (diesel oil)	1	≈0	15	1	<1	<<1	<<1	1
End use:								
Car with catalyst (3.4 MJ_{fuel}/vkm)	65	≈0	130	480	195	(30)	(20)	76
Urban bus with catalyst (18.3 MJ_{fuel}/vkm)	65	≈0	220	135	55	nd	nd	≥68
			TOTAL for car		(field propane)			83
					(refinery ")			90
			TOTAL for bus		(field propane)			≥75
					(refinery ")			≥82

nd = no data

Data from the above table are illustrated in Figures 4.5 and 4.6.

4.3 Methane

The emissions related to vehicle use are based on measurements from laboratory test procedures with natural gas as the fuel. There are almost no data at all from biogas vehicles. However, these emissions can be assumed to be rather similar to those from natural gas with some exceptions. Carbon dioxide being emitted from a biogas vehicle is not of a fossil origin, and so will not increase the net emissions of CO_2 to the atmosphere. Also, biogas does not have any heavier hydrocarbons, which means that the NOx-levels theoretically could be somewhat lower. Concerning unregulated emissions, such as PAC and benzene, these are estimated not to exist in biogas emissions. This affects the mutagenicity level which then could be close to zero.

Table 4.3.1 below shows the emission figures for two defined categories of vehicles with feedback control/3-way catalysts.

Table 4.3.1 Projected emissions from methane vehicles with feedback control/3-way catalysts.

Compound Category	CO_2	CO	NMHC	NO_x	Part.	CH_4	N_2O
	-------------	-------------	g/vkm	-------------	-------------	-------------	mg/vkm
Car with cat./CNG	174	1.5	0.03	0.4	-	0.6	nd
Ditto with biogas	180	"	-	"	"	"	"
Urban bus/CNG	1035	3.1	0.33	5.5	0.05	2.9	nd
Ditto with biogas	1080	"	-	"	"	"	"

continued

Compound	ethene, propene	benzene	form-, aldehyde	PAC (Σ14)	mutagenicity
	--------	mg/vkm	---------	µg/vkm	rev/vm
Car with cat./CNG	nd	nd	nd	nd	nd
Ditto with biogas	nd	~0	nd	~0	~0
Urban bus/CNG	nd	nd	nd	nd	nd
Ditto with biogas	nd	~0	0.1	~0	~0

4.3.1 Natural gas

It is now possible to obtain the total emission figures from the entire fuel chain of natural gas, Table 4.3.2 (see appendix 4.3 for details). The data are illustrated in Figure 4.7 and 4.8.

The emissions from the distribution and compression operations are calculated to be produced in a natural gas fueled power plant with an efficiency of 50 %.

Besides the regulated emissions, it is also important to know the emissions of greenhouse gases. The emissions of methane and other gases are converted to carbon dioxide equivalents by use of the factors in Table 2.3, section 2.2.3.

Table 4.3.2 Emissions in the entire fuel chain per MJ motor fuel. Natural gas - CNG.

Compound **Step (fuel)**	**CO_2** g/MJ_{fuel}	**SOx**	**NOx**	**CO** --------mg/MJ_{fuel}--------	**NMHC**	**CH_4**	**N_2O**	**ΣCO_2-equiv.** g/MJ_{fuel}
Extraction/ preparation (wet gas)	1.8	<<1	8.4	3.2	1.5	64 1)	<<1	3
Processing (wet gas)	1.2	<<1	5.6	2.1	1.0	62 1)	<<1	2.5
Distribution/ end compress. (electricity)	5.0	-	1.8	-	0.3	62 1)	0.5	6.5
End use:								
Car with cat. (3.1 MJ_{fuel}/vkm)	56	<<1	130	480	10	190	nd	62.5
Urban bus with cat. (18.5 MJ_{fuel}/vkm)	56	<<1	300	170	18	160	nd	62
TOTAL for car								74.5
TOTAL for bus								74

1) 1 % methane losses and leakage included, equally split on the three first steps.

4.3.2 Biogas

Emissions from biogas vehicles are assumed to be the same as for natural gas vehicles except for carbon dioxide and non-methane hydrocarbons. This is due to the similarity of biogas and natural gas with methane as the main component in both cases. Table 4.3.1 is therefore valid except for fossil carbon dioxide, which is not emitted from biogas vehicles.

The biggest amounts of emissions are created in the conversion step due to the losses of methane. Cultivation/harvesting and transports of the crop to and residues from the digester plant contribute with mainly CO_2 and NO_x. The internal generation of process energy for conversion, gas purification and compression, mainly electricity, gives a small contribution. The methane lost in the purification is recycled as fuel to the power generation unit and will therefore not contribute with any CH_4 emissions.

The emissions in the whole fuel chain are summarized in Table 4.3.3, in which also the greenhouse gases are converted to CO_2 equivalents using the factors in Table 2.3 (section 2.2.3). See appendix 4.3 for details. The data are illustrated in Table 4.9 and 4.10.

Table 4.3.3 Emissions in the entire fuel chain per MJ_{biogas}. Biogas from lucerne with biogas as process fuel.

Compound	CO_2	SOx	NOx	CO	NMHC	CH_4	N_2O	ΣCO_2-equiv.
Step	g/MJ_{fuel}	--------mg/MJ_{fuel}	----------					g/MJ_{fuel}
Cultivation/ harvesting	3	-	42	8	5	<<1	<1	3.5
Transports	3	-	42	3	1	<<1	<1	3.5
Conversion	(9)	-	13	4	-	607	nd	13
Purification/ compression	(23)	-	14	4	7	-	nd	0.2
Distribution	1	-	1	<1	-	<1	nd	1
End use:								
Car with cat. (3.1 MJ_{biogas}/vkm)	(58)	-	130	480	10	190	nd	6.5
Urban bus with cat. (18.5 MJ_{biogas}/vkm)	(58)	-	300	170	18	160	nd	6
					TOTAL for car			28
					TOTAL for bus			27

( ) from biomass, not included in total

4.4 Methanol

Most of the methanol-fueled development and prototype cars have used M85 or M90, i.e. methanol with 15 vol% gasoline or 10 % hydrocarbon fraction. M100 has been used in most heavy duty vehicles with diesel engines. Here it is assumed that M100 will be the ultimate methanol fuel and corresponding engines will be developed to take advantage of the full potential for low harmful emissions. Blending components will be used for denaturation, ignition aid (optional for diesel engines), and lubricity improvement in low concentrations.

The low vapor pressure of methanol compared to gasoline reduces evaporative losses, which has been confirmed in vehicle tests (SHED, sealed house evaporation determination) yielding values of only a fraction of the limit value (2 g/test). This would be true also for running losses not measured in the test. Moreover, the atmospheric reactivity of the methanol vapor is only about a fifth of the reactivity of gasoline vapors. (Addition of hydrocarbons to the methanol increases the vapor pressure and evaporative losses and hydrocarbons appear in the vapor phase increasing the reactivity of the vapors. Intermediate blends, which can appear in the fuel tanks of gasoline/methanol flexible vehicles, can have particularly high vapor pressures.)

Exhaust emissions from cars have hitherto been measured mostly with prototype engines operated on M85 and in a few instances with M100 development engines. Projected in-use emissions based on the test results are shown in Table 4.4.1 below. Future advanced catalytic clean-up systems (for instance with electric preheating) will give lower emissions in the long term according to test work.

Hydrocarbon emissions constitute only a few percent of total organics and are mainly methane. Older measurements indicated that emissions of olefins (ethene, propene) are extremly low with M100-fuel, benzene emissions are nil, and only traces of PACs and particulate mutagenicity were found (probably of lubrication oil origin). A typical component, excepting unburned methanol, in exhaust gases from methanol-fueled engines is formaldehyde (hardly any acetaldehyde found), which, like most unburned components, is emitted mainly at cold start and during warm-up.

Substituting diesel oil for methanol will bring some evaporative emissions of fuel vapors, negligible for diesel oil.

In heavy-duty diesel vehicle applications methanol has the potential, supported by many measurements, for major reductions of particulate and NOx emissions. The lowest NOx-values (about a third of the diesel oil counterpart) have been obtained with two-stroke engines having a kind of "internal EGR" due to the action of the scavenging air on the exhaust gas. A wide range of emission levels has been shown for emissions of CO and unburned fuel in tests with several different engines, suggesting that performance will strongly depend on design. Oxidation catalysts will be needed for low emission levels. Projected data are shown in Table 4.4.1.

Data on unregulated emissions are still very scarce. In tests with development versions of M100-fueled heavy duty diesel engines, emissions of light hydrocarbons were dominated by methane (≥75 % in CBD- and EPA bus transient test cycles with a glow plug assisted engine) with smaller amounts of ethene and propene. Using an oxidation catalyst on a spark assisted engine reduced methane to 23 and 79 mg/km (bus and CBD cycle respectively) with alkenes below detection limit.

Particulate and PAC emissions are very low from alcohol-fueled diesel engines, and it is questionable if there are any fuel originating particles or PACs at all, but only of crankcase origin. The mutagenicity of both particle-bound and semivolatile PAC were several times lower compared to diesel oil operation. Use of an oxidation catalyst reduced mutagenicity considerably to levels of 5-25 rev/m for the different bacteria systems used, and the semivolatile phase often showed no significant mutagenicity at all.

Aldehyde emissions from later versions of alcohol-fueled diesel engines have been measured to a few hundred mg/km, i.e. at or below the regulatory limit in California (100 mg/bhph). With methanol, formaldehyde represents ≥90 % of the total aldehydes. The oxidation catalyst can reduce aldehydes to <100 mg/km at transient test cycles and there are examples of almost no aldehyde emission at all. It seems, however, important that engine and catalyst are well matched. The present status of development at an U.S. engine manufacturer (Detroit Diesel Corp.) for production-ready engines is a formaldehyde emission level reduction from 80 to 40 mg/bhph by use of oxidation catalyst.

Table 4.4.1 Projected emissions from methanol-fueled vehicles.

Compound Category	CO_2	CO	NMHC	MeOH	Part.	NOx	CH_4	N_2O
	g/vkm						mg/vkm	
Car with catalyst	210	6	0.02	1	-	0.4	20	nd
Urban bus with catalyst	1145	2	0.02	3	0.1	8	50	nd

continued

Compound Category	ethene, propene	benzene	formaldehyde	PAC (Σ14)	mutagenicity
	mg/vkm			µg/vkm	rev/vm
Car with catalyst	2	0	10	2	<1
Urban bus with catalyst	15	≈0	100	nd	?

nd = no data

Estimated emissions in the whole fuel chain from natural gas recovery and biomass (Salix) cultivation respectively to end use in otto engines in cars and and diesel engines in buses are given in Table 4.4.2 and 4.4.3 (see appendix 4.4 for details). In the tables also the total greenhouse gases calculated as CO_2-equivalents have been included, using the conversion factors in Table 2.3, section 2.2.3. Methanol is converted to hydrocarbon equivalents using a factor 0.19 for relative reactivity.

Table 4.4.2 Emissions in the whole fuel chain per MJ_{MeOH}(methanol) Natural gas (NG) to methanol.

Compound Step (fuel)	CO_2	SOx	NOx	CO	HCE	CH_4	N_2O	ΣCO_2-equiv.
	g/MJ_{MeOH}	mg/MJ_{MeOH}						g/MJ_{MeOH}
NG recovery (wet NG)	1.8	<1	8	5	2	90	<<1	4
Conversion (purge gas)	8	<1	110	20	20	44	<1	10
Sea transport (bunker C-oil)	1	17	34	1	2	<<1	<<1	1.5
Distribution (diesel oil)	1	≈0	10	<1	4	<<1	<<1	1
End use:								
Car with catalyst (3.05 MJ/vkm)	69	0	130	2000	70	7	nd	≥77
Urban bus with catalyst (16.6 MJ/vkm)	69	0	480	120	35	3	nd	≥73
				TOTAL for car				≥93
				TOTAL for bus				≥89

nd = no data

Table 4.4.3 Emissions in the whole fuel chain per MJ$_{MeOH}$(methanol) Biomass to methanol.

Compound Step	CO_2	SOx	NOx	CO	HC	CH_4	N_2O	ΣCO_2-equiv.
	g/MJ$_{MeOH}$	-------- mg/MJ$_{MeOH}$ ----------						g/MJ$_{MeOH}$
Cultivation, harvest	10.5	≈1	70	16	10	nd	0.3	≥11
Transport	2	≈0	32	2	1	<<1	<1	2
Conversion	(90)	3	10	18	8	nd	nd	≥0.2
Distribution	1.4	≈0	21	1	4	<<1	<1	1.5
End use:								
Car with catalyst (3.05 MJ/vkm)	(69)	0	130	2000	70	7	nd	8
Urban bus with catalyst (16.6 MJ/vkm)	(69)	0	480	120	35	3	nd	4
					TOTAL for car			≥23
					TOTAL for bus			≥19

nd = no data; ( ) from biomass, not included in total

Use of silviculture tree residues as feedstock will only slightly affect the first figure line of Table 4.4.3 (see appendix 4.4) but will not change the overall picture.

The data in the tables above are given in Figure 4.11 and 4.12 for the natural gas case and in Figure 4.13 and 4.14 for the biomass case.

4.5 Bio-ethanol

Much of what is said about methanol (4.4) is generally applicable to motor alcohols, i e also to ethanol with only minor differences. Data on emissions from ethanol-fueled vehicles are only available for urban buses, which have been the main target fleet vehicles. Tests with the prototype vehicles (predecessors to the new 30 bus fleet operating in Stockholm) using the German bus cycle have given exhaust emissions as shown in Table 4.5.1, which also gives the estimated range for the new motor generations (appendix 4.5).

The emissions in the whole fuel chain have been summarized in Table 4.5.2 for the case with wheat as feedstock and straw as process fuel and in Table 4.5.3 and 4.5.4 the cases with Salix/ Iogen-process and tree residues/CASH-process respectively (for details see appendix 4.5). The data are illustrated in Figures 4.15 - 4.20.

Table 4.5.1. Emissions for ethanol-fueled buses. Bus cycle driving.

Compound	CO_2	CO	"HC"	NOx	Part.	CH_4	N_2O
	g/vkm					mg/vkm	
Without catalyst	1145	12.6	2.6	14.3	0.17	nd	nd
With catalyst	1190	2.0- -1.5	0.7- -0.5	12.9- -9.0	0.11	nd	nd

nd = no data

continued

ethene propene	formaldehyde acetaldehyde	ethyl nitrite	PAC* (Σ14)	Mutagenicity* (TA98-S9)	(TA98+S9)
mg/vkm			µg/vkm	rev/vm	
49 <17	310 420	175	49	110-155	58-104
29 <17	57 82	175	7	135-200	21-26

* in particle and semivolatile phases

Table 4.5.2. Emissions in the whole fuel chain per MJ_{EtOH}(ethanol) Ethanol from wheat. Straw as process fuel.

Step	CO_2	SOx	NOx	CO	"HC"	CH_4	N_2O	ΣCO_2-equiv.
	g/MJ_{EtOH}	mg/MJ_{EtOH}						g/MJ_{EtOH}
Cultivation, harvest	23	0-3	150	40	25	nd	0.8	≥24.5
Grain drying	6	0-2	5	10	1	<<1	1	≥6.5
Transport	2	<1	30	2	1	<<1	<1	2.5
Conversion	(111)	≈20	70	150	60*	nd	nd	≥1.5
Distribution	1	≈0	15	1	4	<<1	<<1	1
End use (urban bus with catalyst, 16.6 MJ/vkm)	(72)	0	540- -775	85- -120	30- -45	nd	nd	≈4.5- -6.5
							TOTAL	≥40- -42

nd = no data ( ) from biomass, not included in total * PAC-emission expected

Note: Values are not corrected for reduced effects elsewhere in production of replaced feed product.

Table 4.5.3. Emissions in the whole fuel chain per MJ_{EtOH}(ethanol) Ethanol (E100) from Salix. Iogen-process.

Compound	CO_2	SOx	NOx	CO	"HC"	CH_4	N_2O	ΣCO_2-equiv.
Step	g/MJ_{EtOH}	--------- mg/MJ_{EtOH} ------------						g/MJ_{EtOH}
Cultivation, harvest	9.5	≈1	63	14	9	nd	nd	≥10
Transport	11	≈0	50	10	7	nd	<<1	11.5
Conversion	(178)	≈40	130	245	115*	nd	nd	≥3
Distribution	1	≈0	15	1	4	<<1	<<1	1
End use Urban bus with catalyst, 16.6 MJ/vkm)	(72)	0	540-775	85-120	30-45	nd	nd	≈4.5-6.5
							TOTAL	≥30-32

nd = no data ( ) from biomass, not included in total * PAC-emissions expected

Table 4.5.4. Emissions from the whole fuel chain per MJ_{EtOH} (ethanol). Ethanol (E95) from tree residues. CASH-process.

Compound	CO_2	SOx	NOx	CO	"HC"	CH_4	N_2O	ΣCO_2-equiv.
	g/MJ_{EtOH}	-------- mg/MJ_{EtOH} -----------						g/MJ_{EtOH}
Silviculture, harvest	11	<1	50	10	7	nd	<<1	11.5
Transport	1	≈0	16	1	<1	<<1	0.5	1.5
Conversion	(128)	≈10	88	77	27*	30	nd	2.5
Distribution	1	≈0	15	1	4	<<1	<<1	1
End use (urban bus with catalyst,16.6 MJ/vkm)	(72)	0	540-775	85-120	30-45	nd	nd	≥4.5-6.5
							TOTAL	≥21-23

nd = no data ( ) from biomass, not included in total * PAC-emission expected

4.6 Vegetable oil

As in chapter 3.6 vegetable oil will here be dealt with as rapeseed oil methyl ester (RME). Most emission data available are for rapeseed oil and RME, used in small diesel engines, in comparison to diesel oil fueling /70,71, 74/. To be able to give a preliminary estimate of emissions from urban buses, the data for these with diesel oil fueled, catalyst equipped, heavy duty engines are adjusted for the differences experienced with the smaller diesel engines. The measurements that are made are based on standard diesel engines without any modifications for the rapeseed oil. Therefore it is plausible that the potential for low emissions are better than the test results show. Table 4.6.1 shows the estimated emissions.

Emissions in the entire fuel chain with end use of RME in an urban bus are given in Table 4.6.2 (for details see appendix 4.6). In the table the total greenhouse gases, calculated as CO_2, have been included using the conversion factors given in Table 2.3, section 2.2.3. The data are illustrated in Figures 4.21-22.

Table 4.6.1 **Preliminary estimated emissions from urban bus fueled by rapeseed oil methyl ester (RME).**

Compound	**CO_2**	**CO**	**HC**	**NOx**	**Part.**	**CH_4**	**N_2O**
Category			**g/vkm**			**mg/vkm**	
Urban bus with catalyst	**1270**	**0.5**	**0.4**	**15-19**	**0.2**	**80**	**nd**

continued

Compound	**ethene, propene**	**benzene**	**form-aldehyde**	**PAC**	**mutagenicity**
		mg/vkm			**rev/m**
Urban bus with catalyst	**40**	**3**	**25**	**?**	**nd**

? = inconclusive data nd = no data

Table 4.6.2 **Estimated emissions per MJ of motor fuel in the fuel chain rape growing to rapeseed oil methyl ester (RME). Biomass as process fuel.**

Compound	**CO_2**	**SOx**	**NOx**	**CO**	**HC**	**CH_4**	**N_2O**	**ΣCO_2-equiv.**
Step	**g/MJ_{RME}**			**mg/MJ_{RME}**				**g/MJ_{RME}**
Cultivation/ harvesting	**21**	**-**	**123**	**25**	**21**	**<<1**	**<1**	**22.5**
Transport	**1**	**-**	**21**	**1**	**1**	**<<1**	**<1**	**1**
Conversion	**(13)**	**3**	**13**	**20**	**9**	**<<1**	**<<1**	**0.5**
End distribution	**1**	**-**	**10**	**<1**	**<1**	**<<1**	**<<1**	**1**
End use (urban bus with cat., 16.6 MJ/vkm)	**(76.5)**	**-**	**900--1145**	**30**	**24**	**5**	**nd**	**7-8.5**
							TOTAL	**32-33**

( ) from biomass, not included in total; nd = no data

4.7 Hydrogen

The combustion of hydrogen is considered to take place in an engine adapted for this purpose. In order to get low NOx emissions water has to be injected in parallel with the hydrogen. A future possible use of hydrogen is in fuel cells for traction of electrically propelled road vehicles. This would give extremely low emissions at end use but is not considered in this study.

There are not yet very many measurements available from well documented tests with the hydrogen fueled vehicles. However, it is a common understanding that hydrogen as a motor fuel is quite favourable to the local environment. Measured and projected emissions have been summarized in Table 4.7.1.

Table 4.7.1 Preliminary projected emissions from hydrogen fueled vehicle.

Compound Category	CO	HC	NOx	Part.	CO_2	CH_4	N_2O
	g/vkm					mg/vkm	
Car (water inj.)	0	0	0.1	0	0	0	nd

continued

Compound Category	ethene, propene	benzene	aldehydes	PAC (Σ14)	mutagenicity (TA98±S9)
	mg/vkm			µg/vkm	rev/vm
Car (water inj.)	0	0	0	0	-

nd = no data

The influence of hydrogen is most evident on emissions of carbon containing species. They are considered non-existing in the table above, but some carbon contents could be there from possible lubricants.

Tentative, estimated values for emissions in the whole fuel chain with end use as liquid hydrogen only, but for electricity from national net and natural gas fueled power plant in the condensing mode resp, in passenger cars are given in Table 4.7.2 and Table 4.7.3 (see appendix 4.7 for details). In the tables also the total greenhouse gases calculated as CO_2-equivalents have been included, using the conversion factors given in Table 2.3, section 2.2.3. The data are illustrated in Figure 4.23 - 26.

Table 4.7.2 **Emissions in the whole fuel chain per MJ motor fuel**
Liquid hydrogen in passenger car
Electricity from hydropower

Compound	**CO_2**	**SOx**	**NOx**	**CO**	**HC**	**CH_4**	**N_2O**	**ΣCO_2-equiv.**
Step (fuel)	**g/MJ_{fuel}**	---------	---------	**mg/MJ_{fuel}**	-----------	-----------	-----------	**g/MJ_{fuel}**
Sea transport (bunker C-oil)	2.5	40	80	1.6	4	<<1	<<1	3.1
Distribution	2.9	<<1	40	2.8	1.4	0.1	0.3	3.3
End use (car water injected, 2.9 MJ_{fuel}/vkm)	0	0	35	0	0	0	nd	0.2
							TOTAL	6.6

nd = no data

Table 4.7.3 **Emissions in the whole fuel chain per MJ motor fuel**
Liquid hydrogen in passenger car
Electricity from NG condensing power plant

Compound	**CO_2**	**SOx**	**NOx**	**CO**	**HC**	**CH_4**	**N_2O**	**ΣCO_2-equiv.**
Step (fuel)	**g/MJ_{fuel}**	---------	---------	**mg/MJ_{fuel}**	-----------	-----------	-----------	**g/MJ_{fuel}**
Electrolysis	210	1.5	110	0	0	0	0	211
Liquefaction	50	0.4	27	0	0	0	0	50
Sea transport (bunker C-oil)	2.5	40	80	1.6	4	<<1	<<1	3.1
Distribution	2.9	<<1	40	2.8	1.4	0.1	0.3	3.3
End use (car water injected, 2.9 MJ_{fuel}/vkm)	0	0	35	0	0	0	nd	0.2
							TOTAL	257

nd = no data

4.8 Electricity

The only emissions in this energy chain originate from the generation of electricity. The two cases studied give emissions as presented in Table 4.8.1 and 4.8.2 below and also in Figure 4.27 and 4.28. For details see appendix 4.8.

Table 4.8.1 Emissions in the whole fuel chain per MJ motor fuel
Electricity from Swedish average generation set up

Compound Step	CO_2 g/MJ_{fuel}	SOx --------- mg/MJ_{fuel} -----------	NOx	CO	HC	CH_4	N_2O	ΣCO_2-equiv. g/MJ_{fuel}
Power generation	15	21	21	3	<<1	nd	nd	15.2
							TOTAL	15.2

nd = no data

Table 4.8.2 Emissions in the whole fuel chain per MJ motor fuel
Electricity from natural gas

Compound Step	CO_2 g/MJ_{fuel}	SOx --------- mg/MJ_{fuel} -----------	NOx	CO	HC	CH_4	N_2O	ΣCO_2-equiv. g/MJ_{fuel}
Power generation	177	1.2	93	≈0	≈0	≈0	≈0	178
							TOTAL	178

Regarding electric hybrid vehicles of a series design and utilizing a motor/generator device, there is, like as in general when operating a combustion engine, a choice between minimum energy demand and minimum emission of some component e g NOx. For the former alternative, the NOx emission is somewhat higher than for conventional propulsion by combustion engine, while at the latter choice, the NOx emissions can be considerably reduced at the same energy demand. The otto engine has been assessed to have a high potential for development for the use in motor/generator devices for hybrid vehicles.

Electric vehicle propulsion, getting supplied from the common grid via a traction battery, is from the local angle the most favourable vehicle propulsion technique with respect to airborne emissions. Acoustic emissions (traffic noise; not studied here) from EVs are also estimated to be small compared to those from conventional vehicles.

Lately, another type of environment impact from the application of electricity has come to be discussed. This is the effect of time-varying electric and magnetic fields on living tissues. In connection to power distribution and the use of electric appliances, a new type of environment questions, suggestedly categorized by the concept electric hypersensitivity or electric allergy, have appeared. The reasons for the physiological reactions which have come to be named electric hypersensitivity is unclear. However, many individuals who have experienced those reactions are convinced, that they are connected with the exposure to time-varying electromagnetic fields.

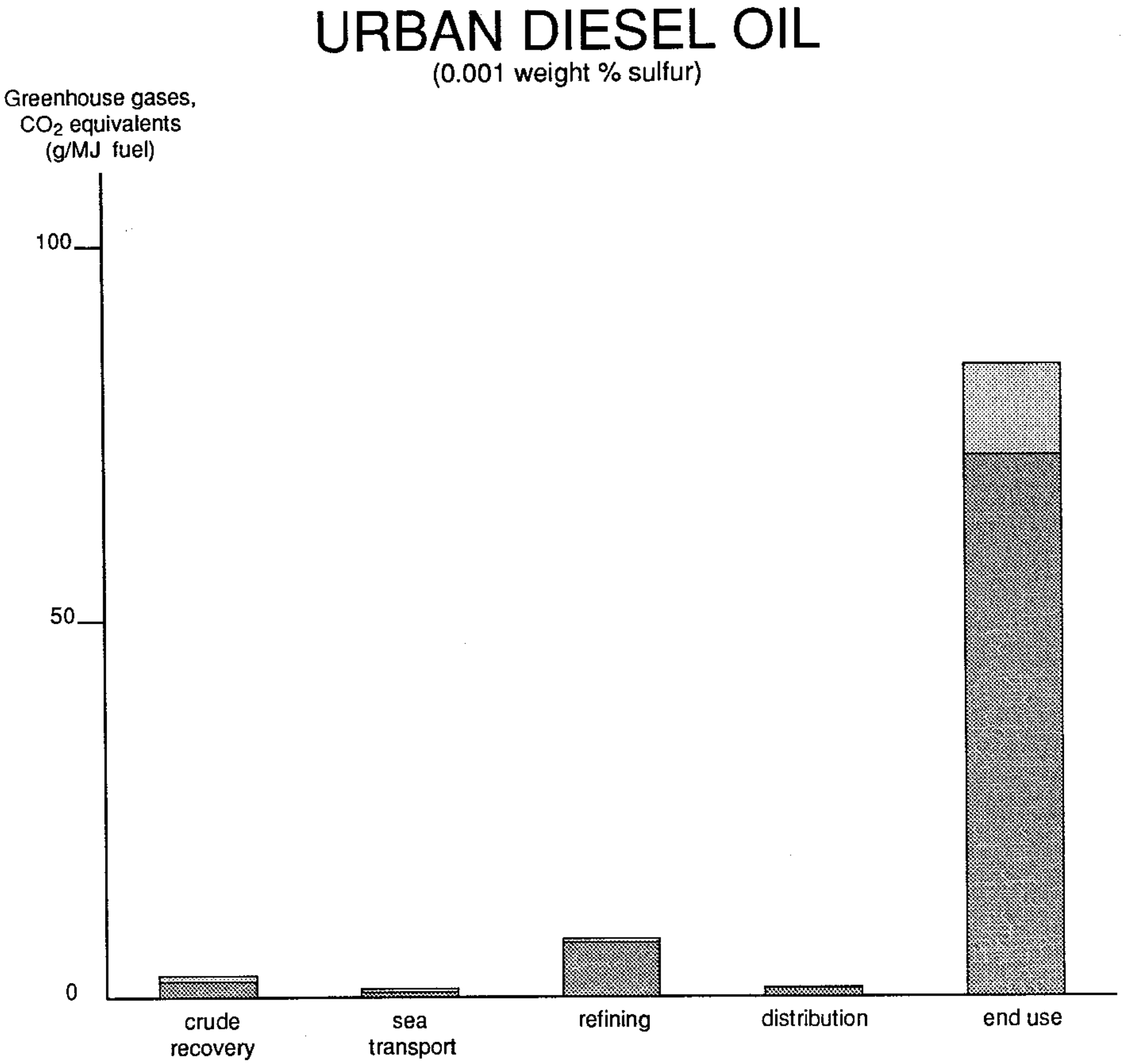

Figure 4.1 Release of greenhouse gases in the fuel chain crude oil recovery to urban diesel oil use in heavy duty diesel bus engine.

▨ fossil CO_2

☐ renewable CO_2

░ other greenhouse gases (methane, N_2O, NOx, other HC)

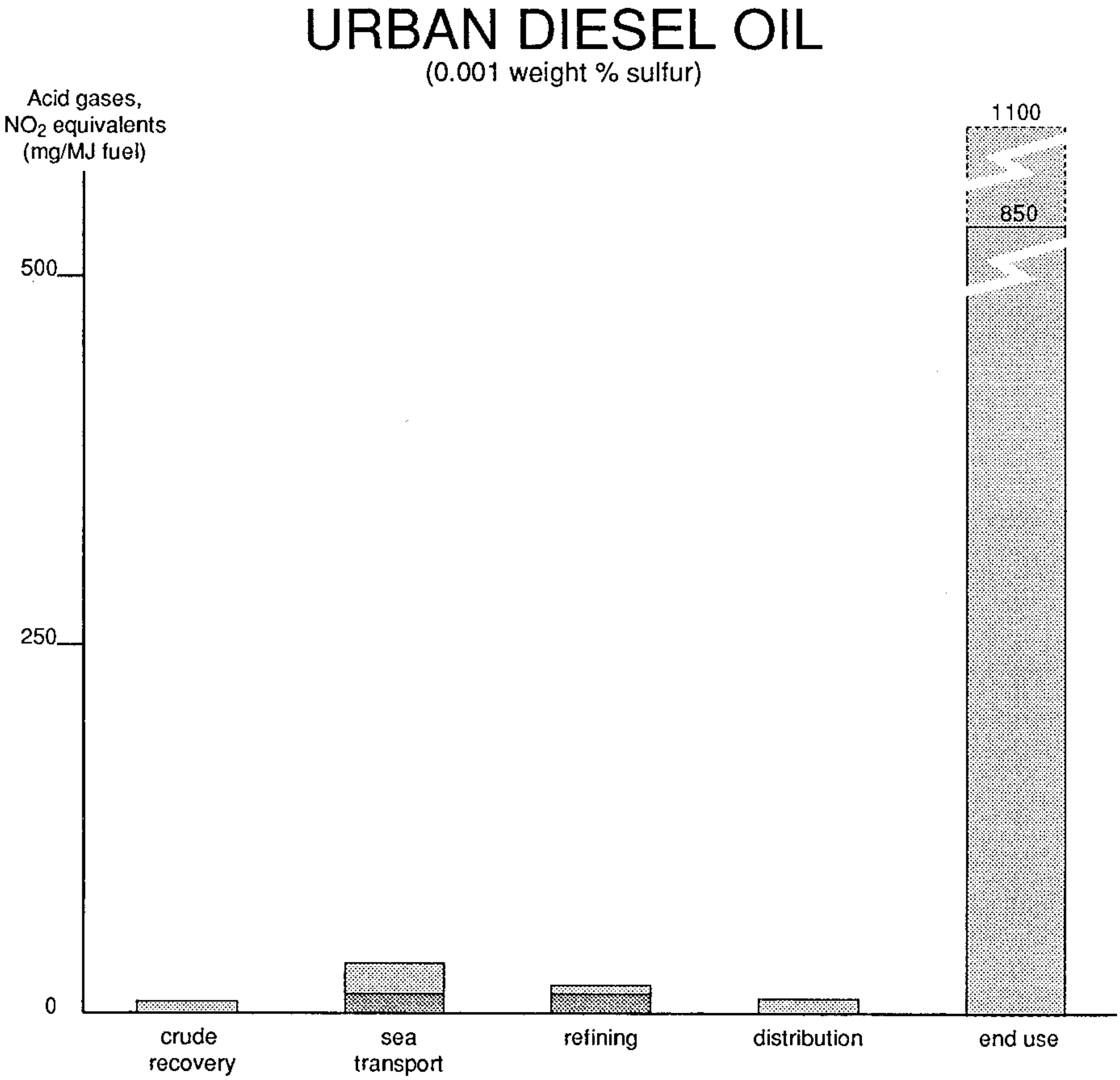

Figure 4.2 Release of acid gases in the fuel chain crude oil recovery to urban diesel oil use in heavy duty diesel bus engine.

░ NOx

▒ SOx

⬚ range (for any shading)

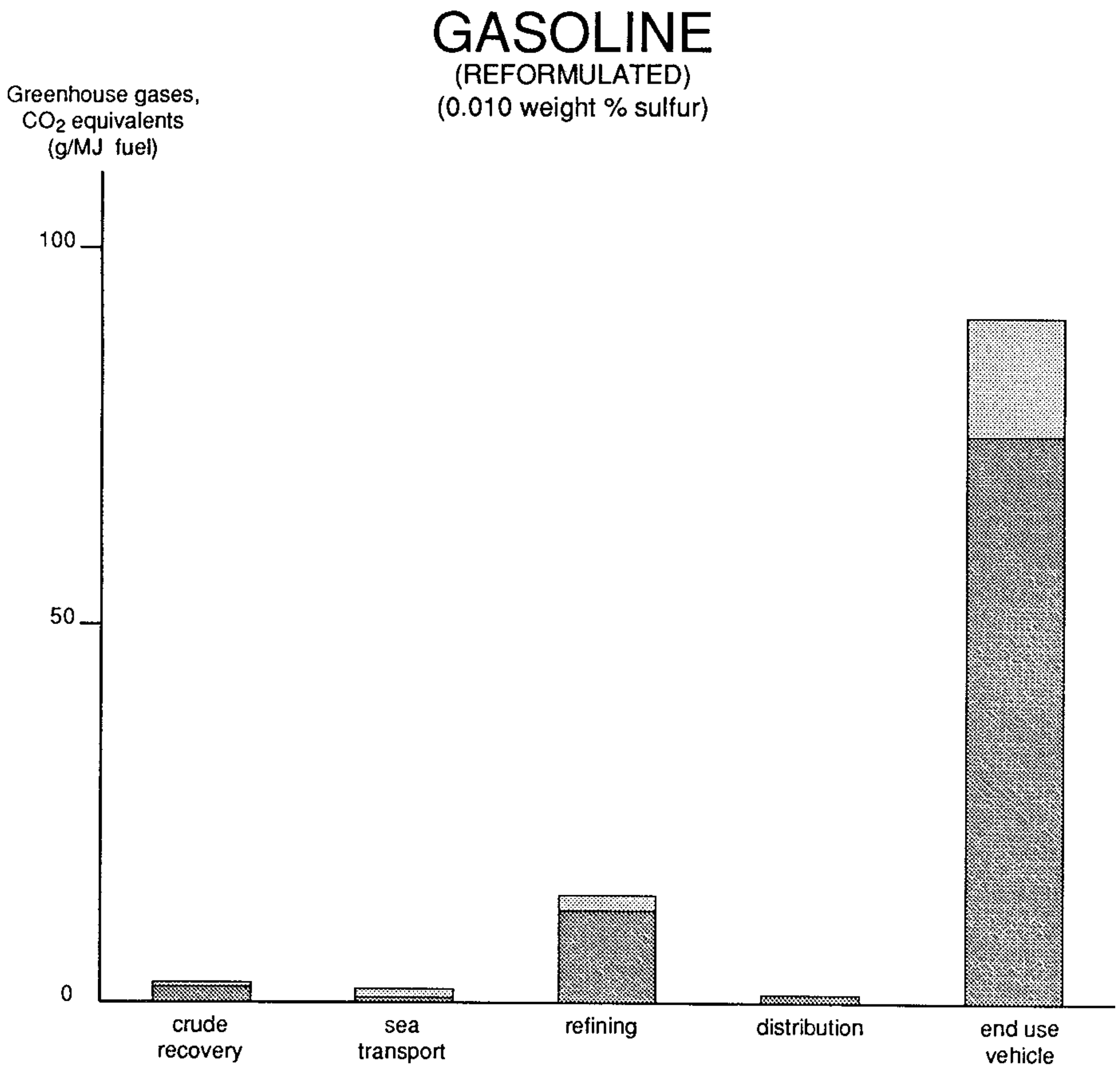

Figure 4.3 Release of greenhouse gases in the fuel chain crude oil recovery to gasoline use in PC otto engine.

▨ fossil CO_2

□ renewable CO_2

░ other greenhouse gases (methane, N_2O, NOx, other HC)

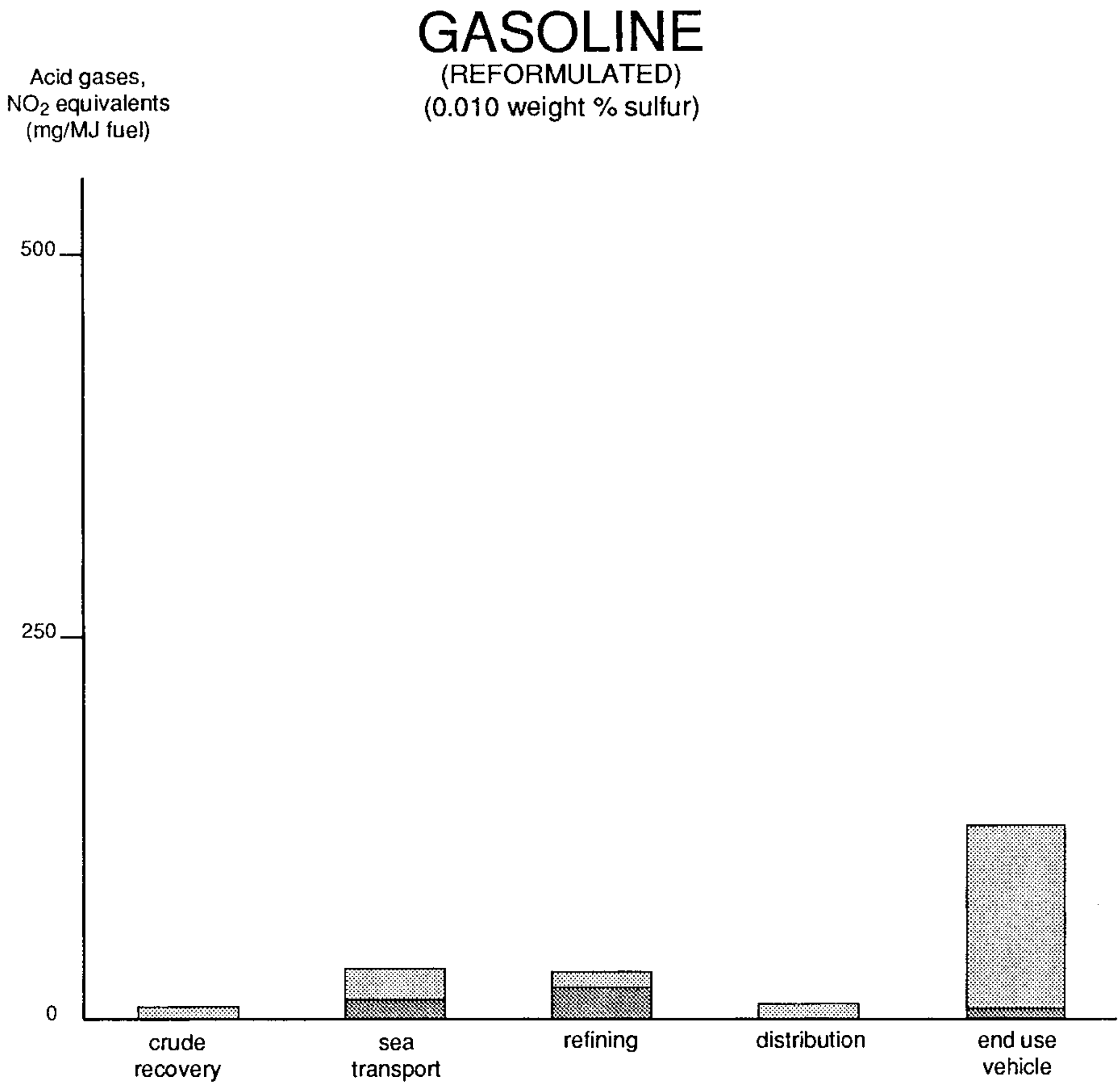

Figure 4.4 Release of acid gases in the fuel chain crude oil recovery to reformulated gasoline use in PC otto engine.

░ NOx

▒ SOx

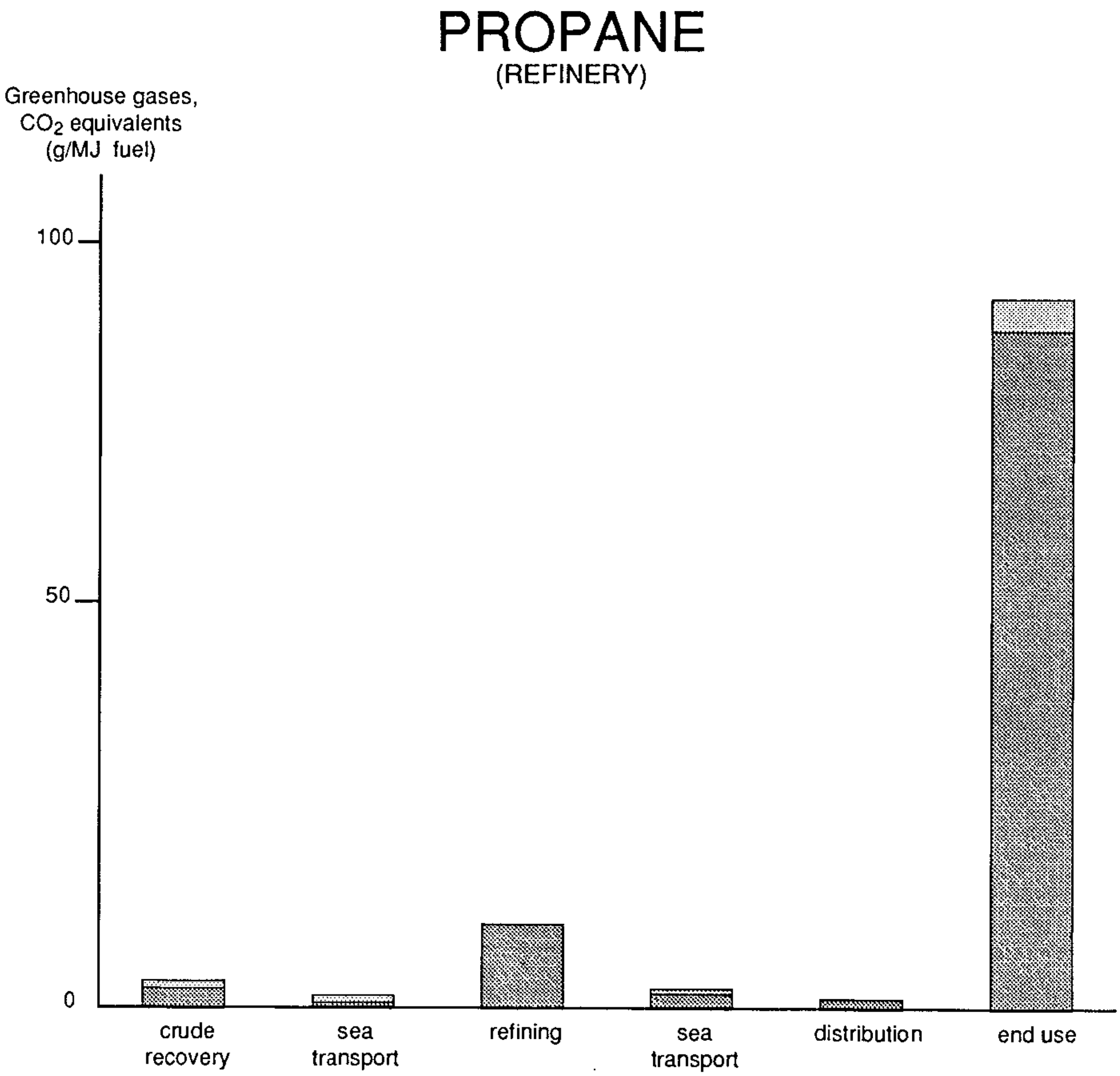

Figure 4.5 Release of greenhouse gases in the fuel chain crude oil recovery to refinery propane use in heavy duty otto bus engine.

▩ fossil CO_2

☐ renewable CO_2

▨ other greenhouse gases (methane, N_2O, NOx, other HC)

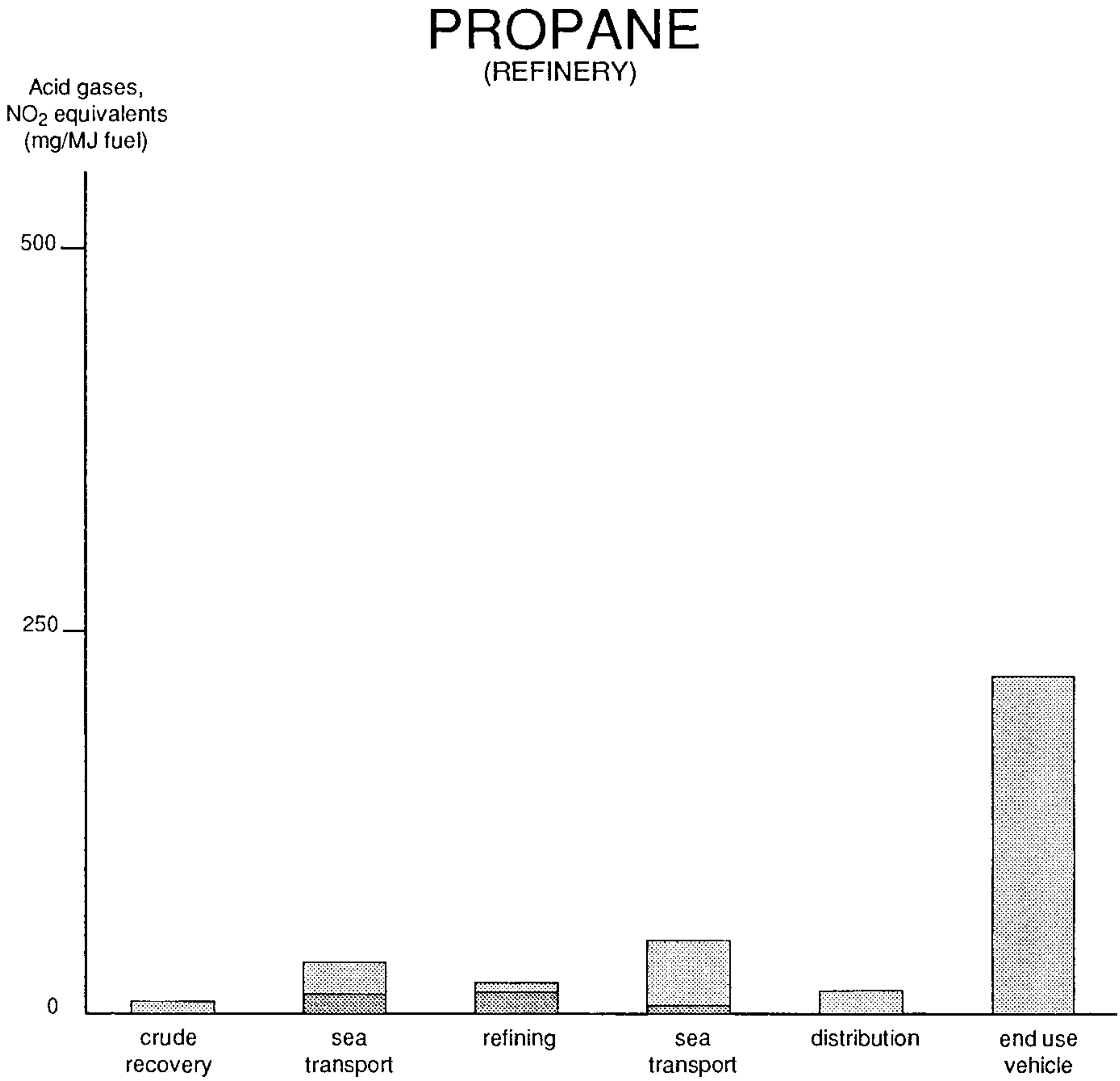

Figure 4.6 Release of acid gases in the fuel chain crude oil recovery to refinery propane use in heavy duty otto bus engine.

░ NOx

▒ SOx

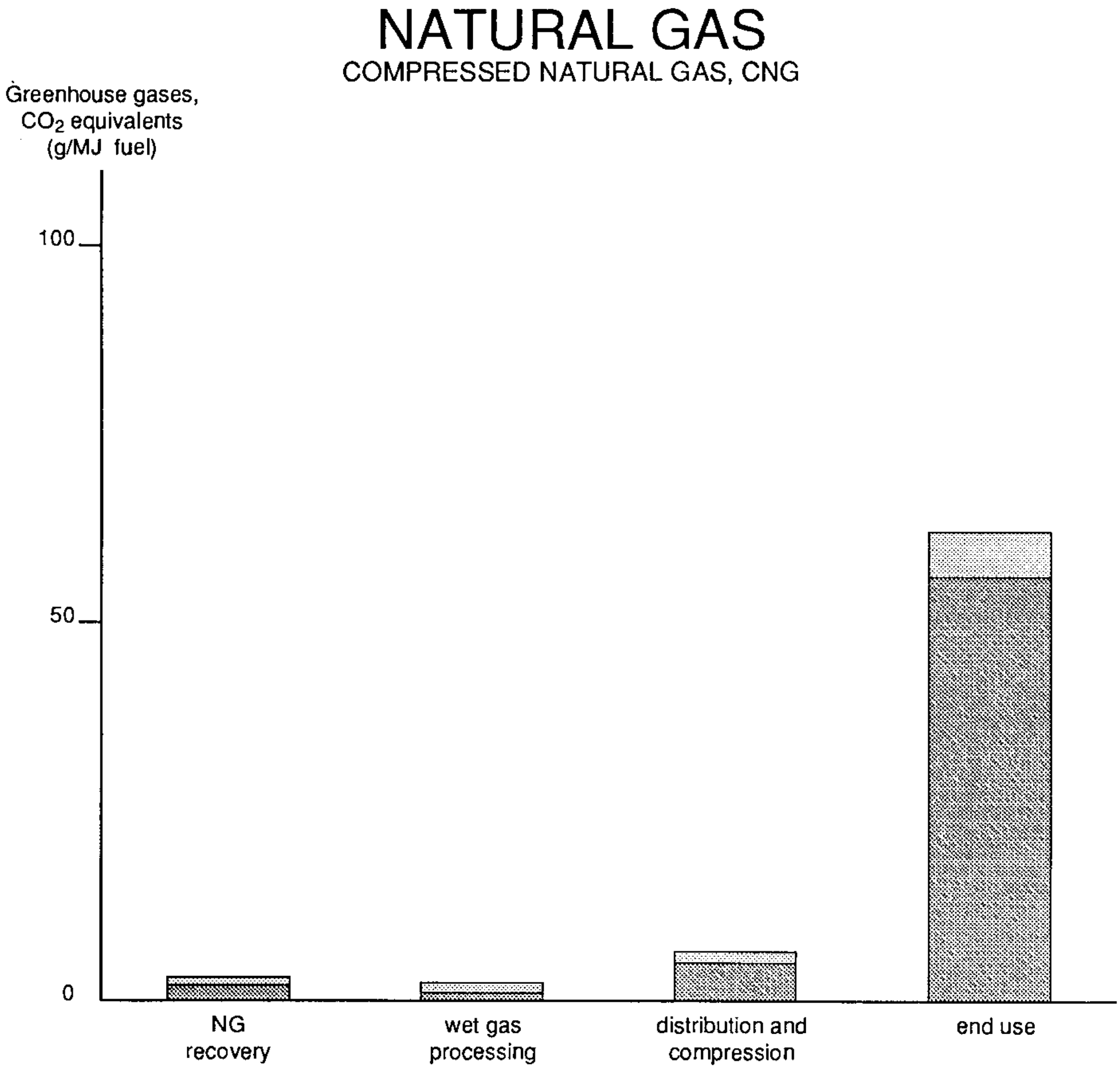

Figure 4.7 Release of greenhouse gases in the fuel chain natural gas recovery to CNG use in heavy duty otto bus engine.

▩ fossil CO_2

☐ renewable CO_2

▒ other greenhouse gases (methane, N_2O, NOx, other HC)

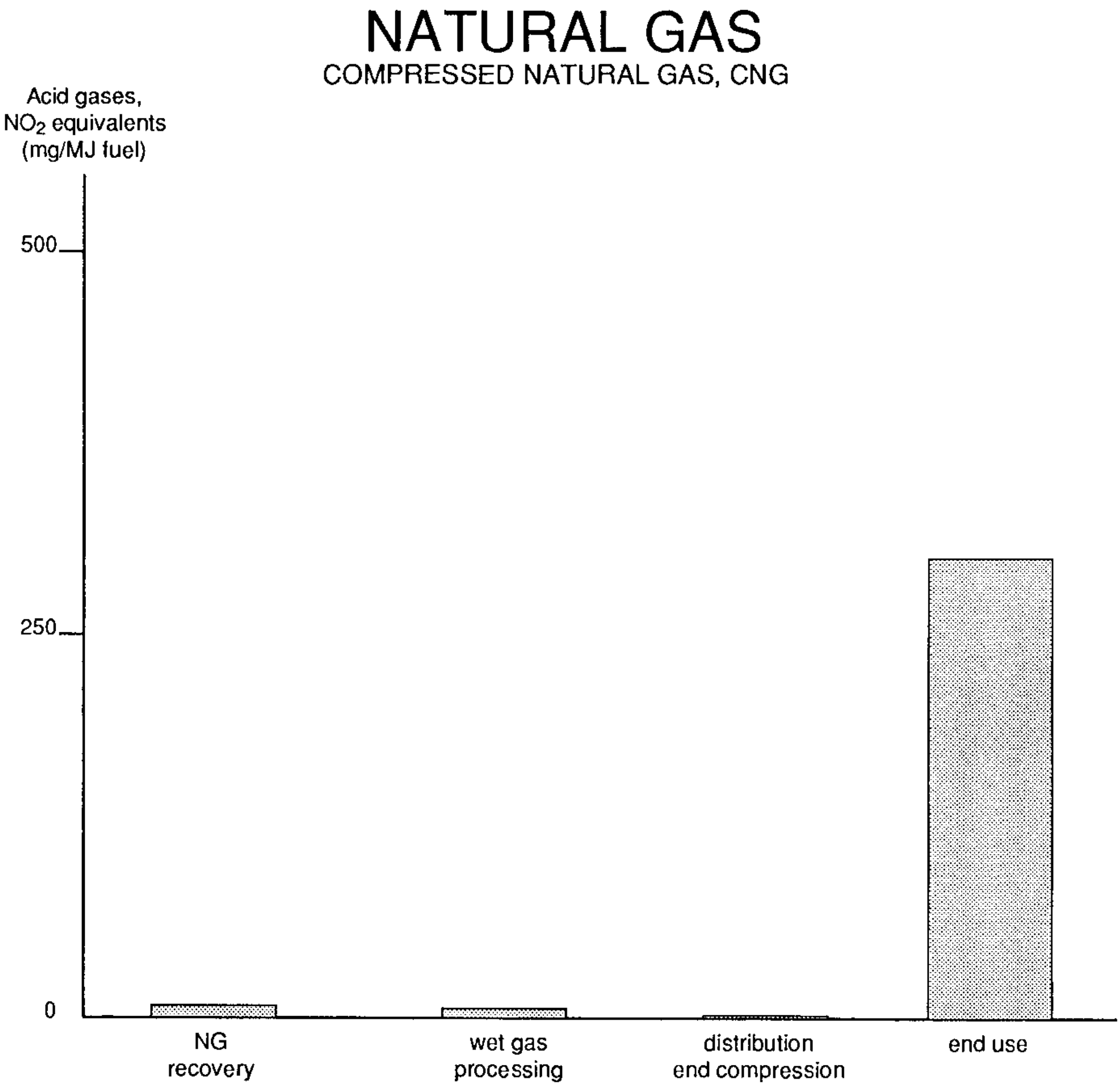

Figure 4.8 Release of acid gases in the fuel chain natural gas recovery to CNG use in heavy duty otto bus engine.

░ NOx

▒ SOx

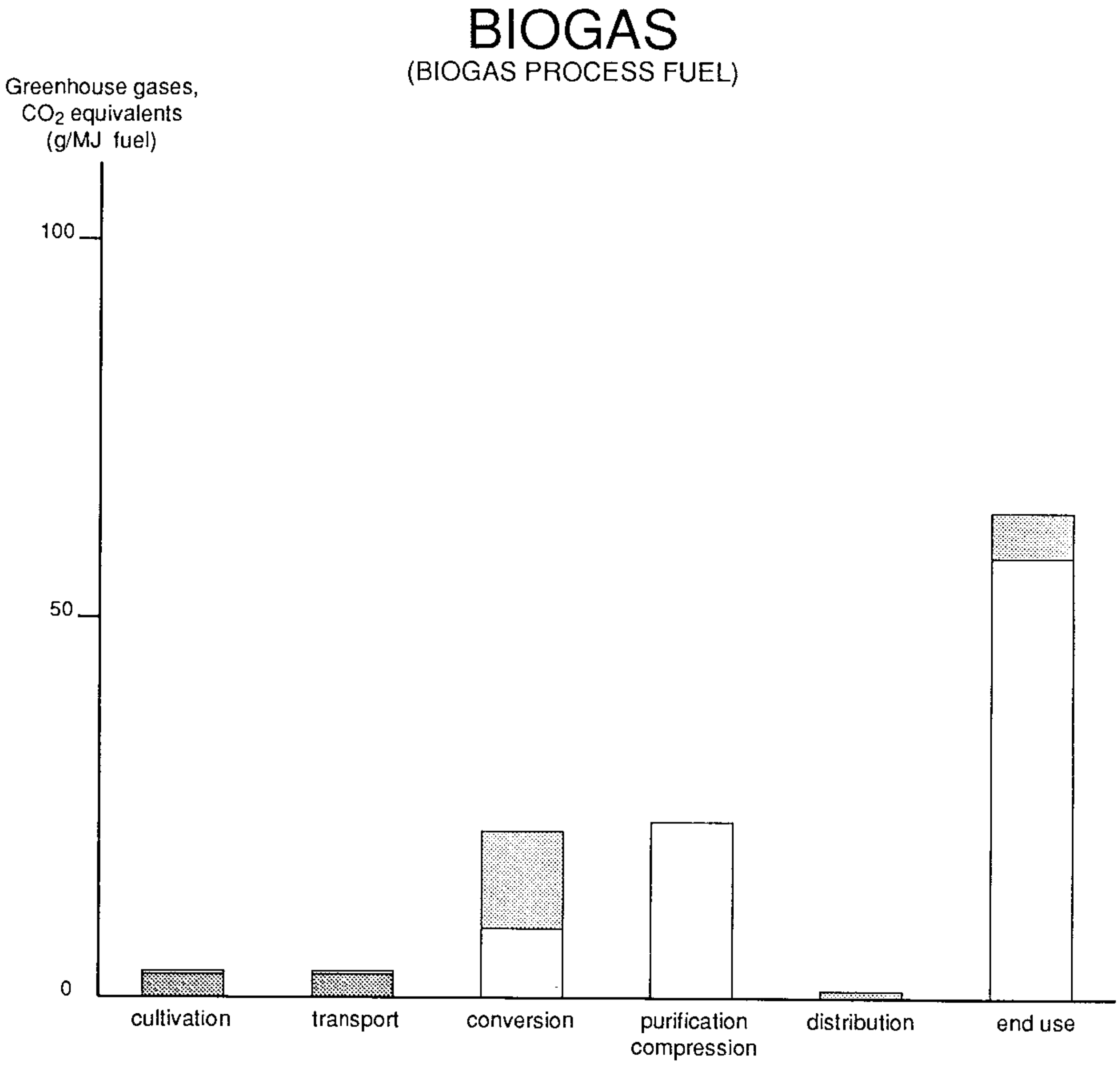

Figure 4.9 Release of greenhouse gases in the fuel chain lucerne growing to compressed methane use in heavy duty otto engine in bus cycle operation (biomass based CO_2 included).

▨ fossil CO_2

☐ renewable CO_2

▨ other greenhouse gases (methane, N_2O, NOx, other HC)

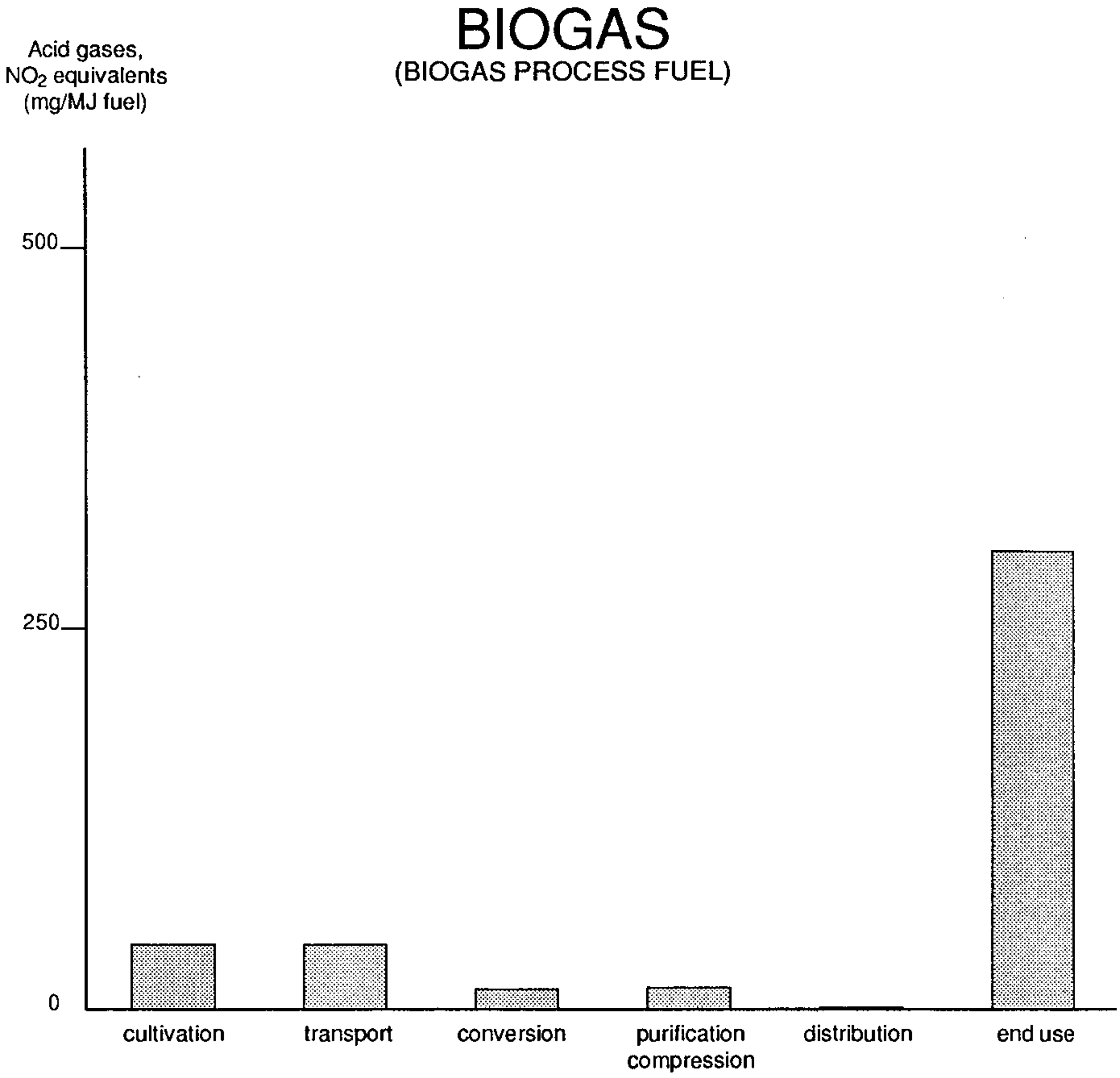

Figure 4.10 Release of acid gases in the fuel chain lucerne to compressed methane use in heavy duty otto bus engine.

░ NOx

▒ SOx

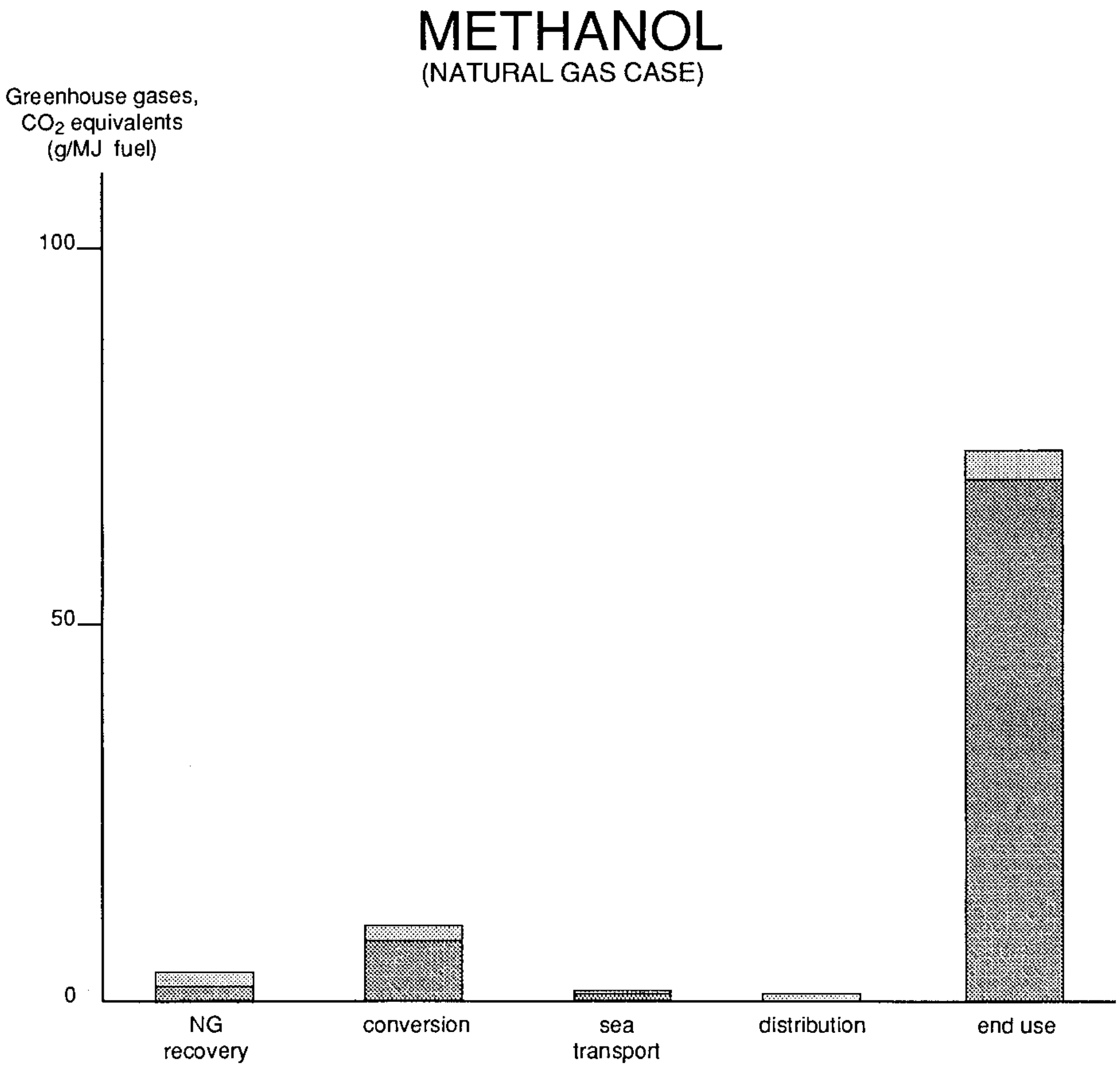

Figure 4.11 Release of greenhouse gases in the fuel chain natural gas recovery to methanol use in heavy duty diesel bus engine.

▨ fossil CO_2

☐ renewable CO_2

▨ other greenhouse gases (methane, N_2O, NOx, other HC)

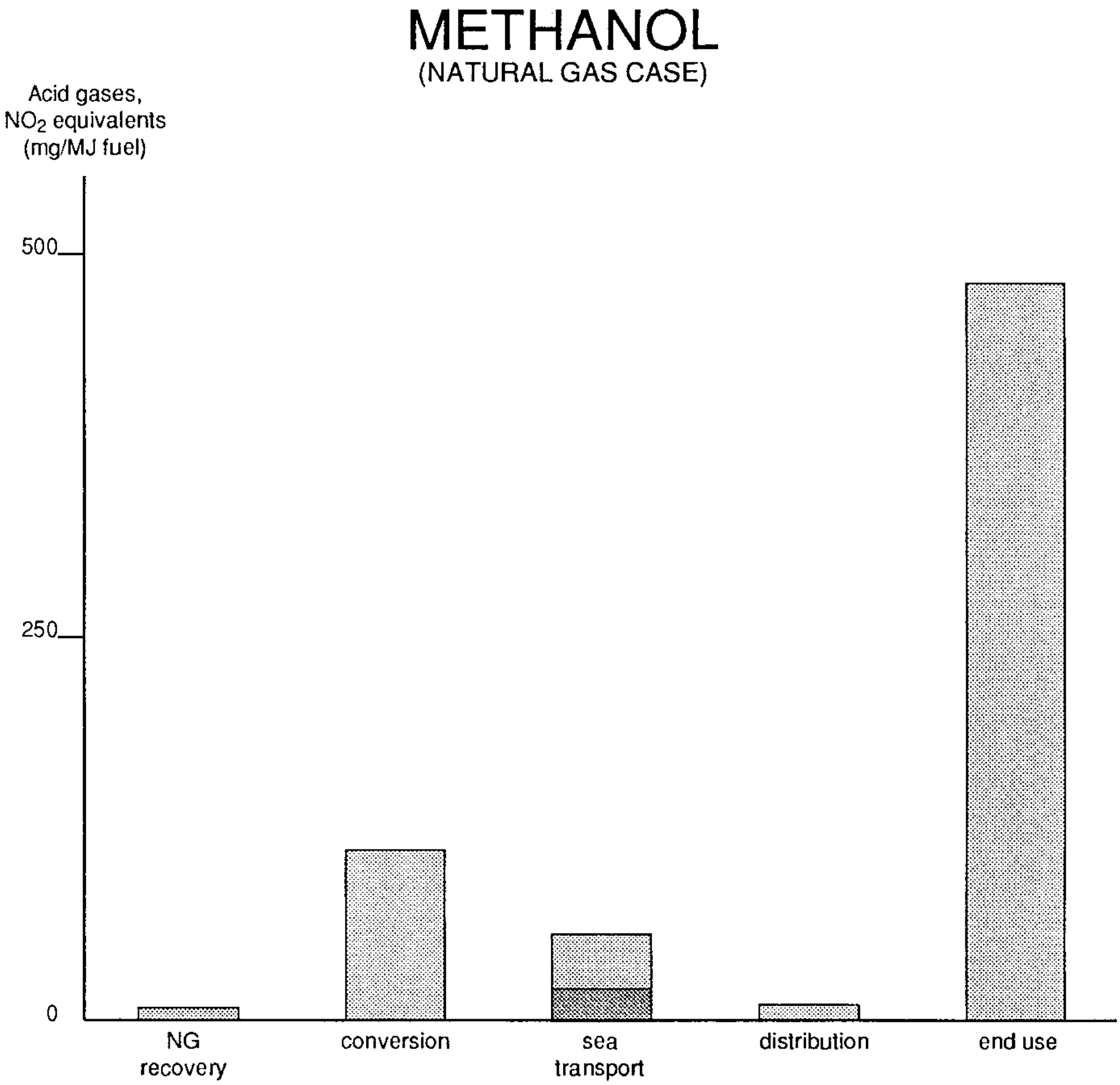

Figure 4.12 Release acid gases in the fuel chain natural gas recovery to methanol use in heavy duty diesel bus engine.

▨ NOx

▩ SOx

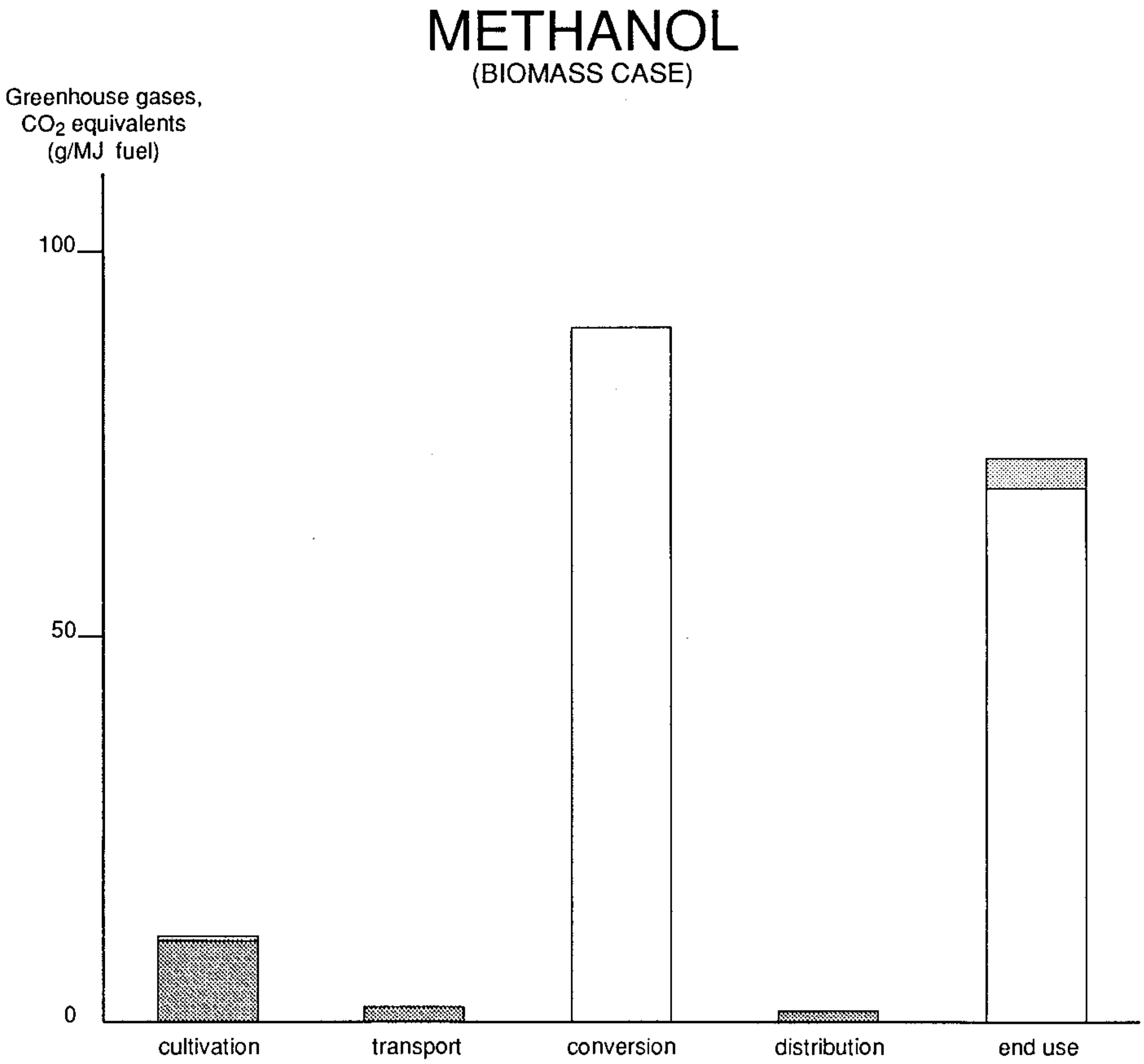

Figure 4.13 Release of greenhouse gases in the fuel chain Salix growing to methanol use in heavy duty diesel bus engine (biomass based CO_2 included).

▩ fossil CO_2

☐ renewable CO_2

░ other greenhouse gases (methane, N_2O, NOx, other HC)

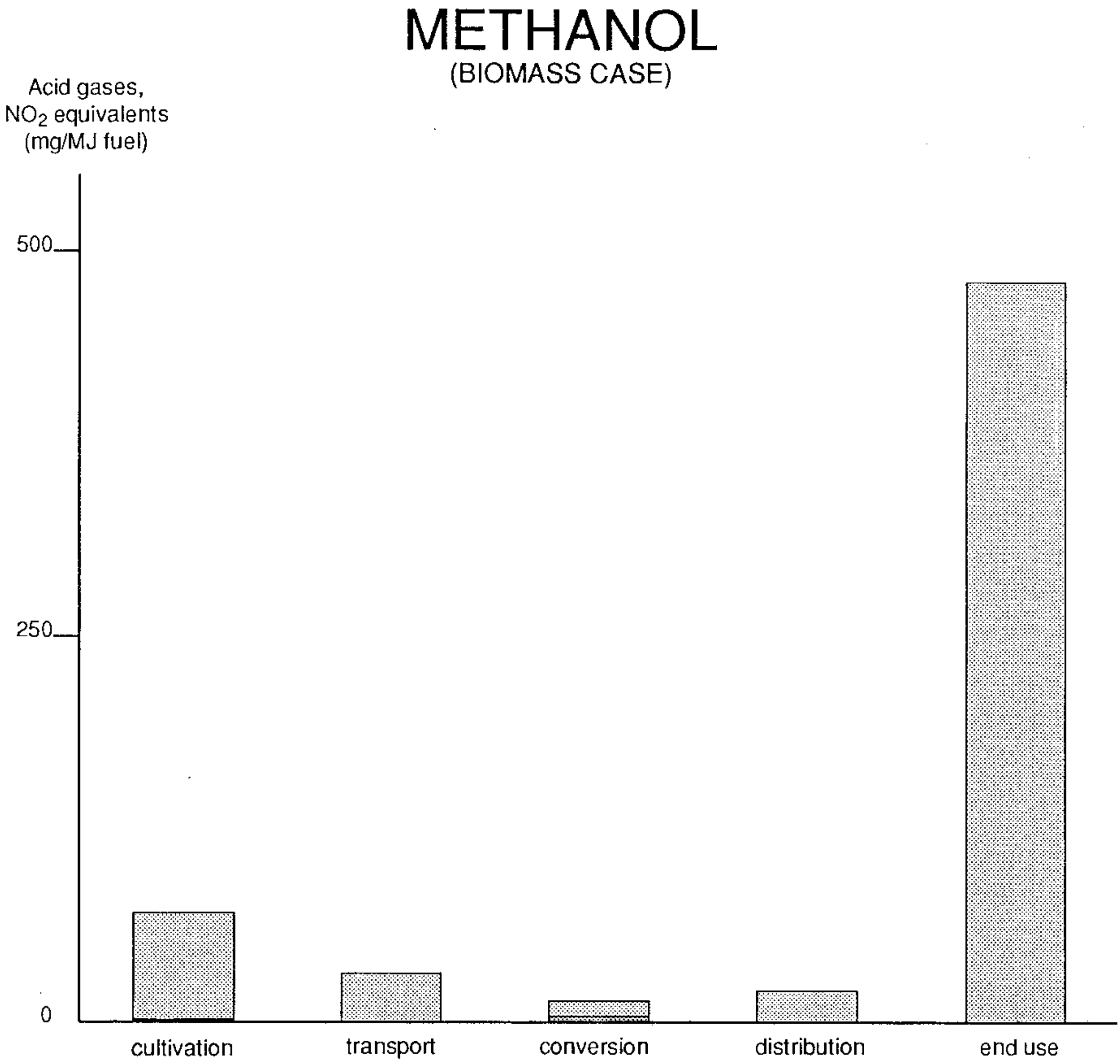

Figure 4.14 Release of acid gases in the fuel chain Salix growing to methanol use in heavy duty diesel bus engine.

▨ NOx

▨ SOx

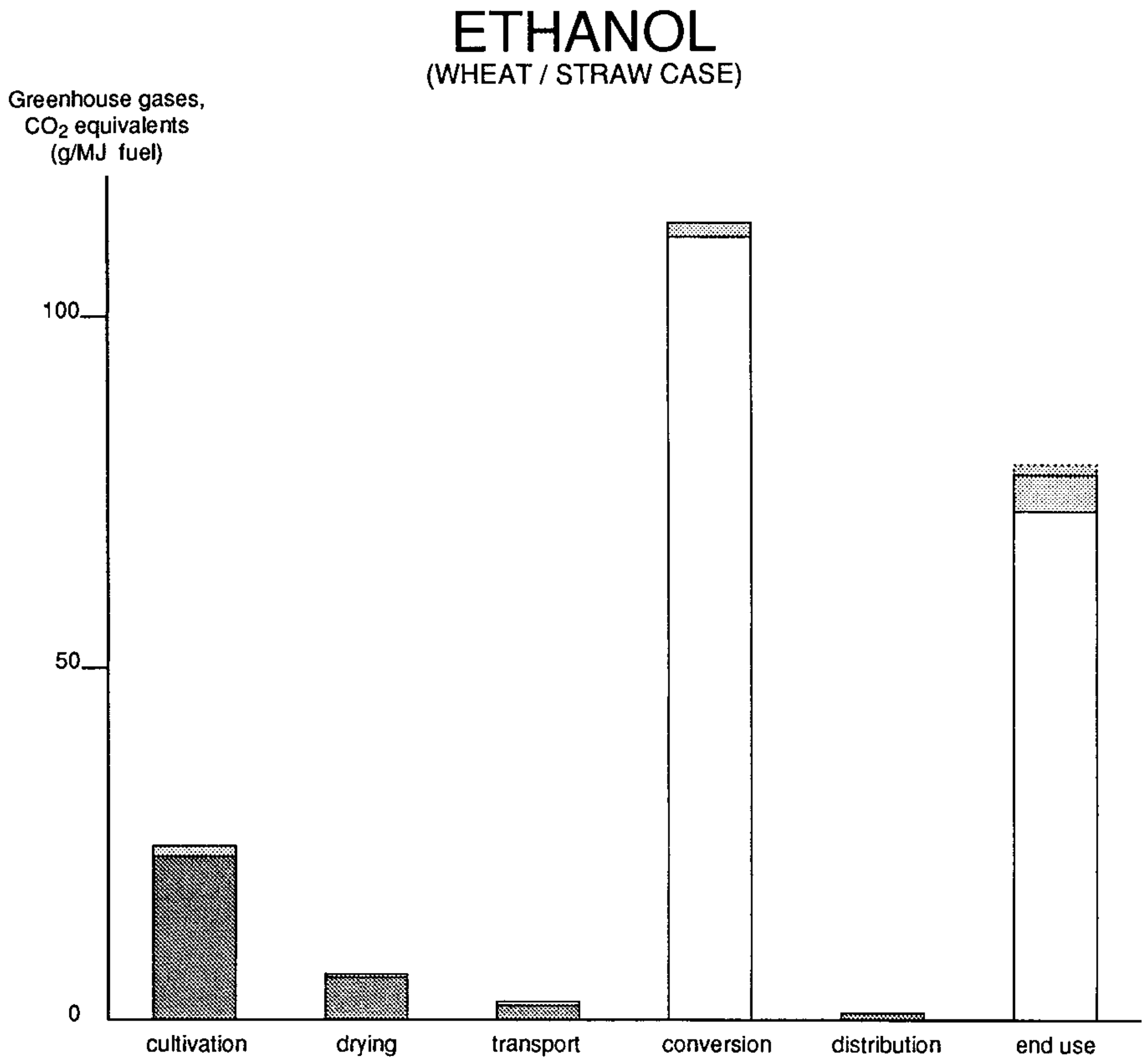

Figure 4.15 Release of greenhouse gases in the fuel chain wheat growing to ethanol use in heavy duty diesel bus engine (biomass based CO_2 included).

▩ fossil CO_2 ░ range (for any shading)

☐ renewable CO_2

▒ other greenhouse gases (methane, N_2O, NOx, other HC)

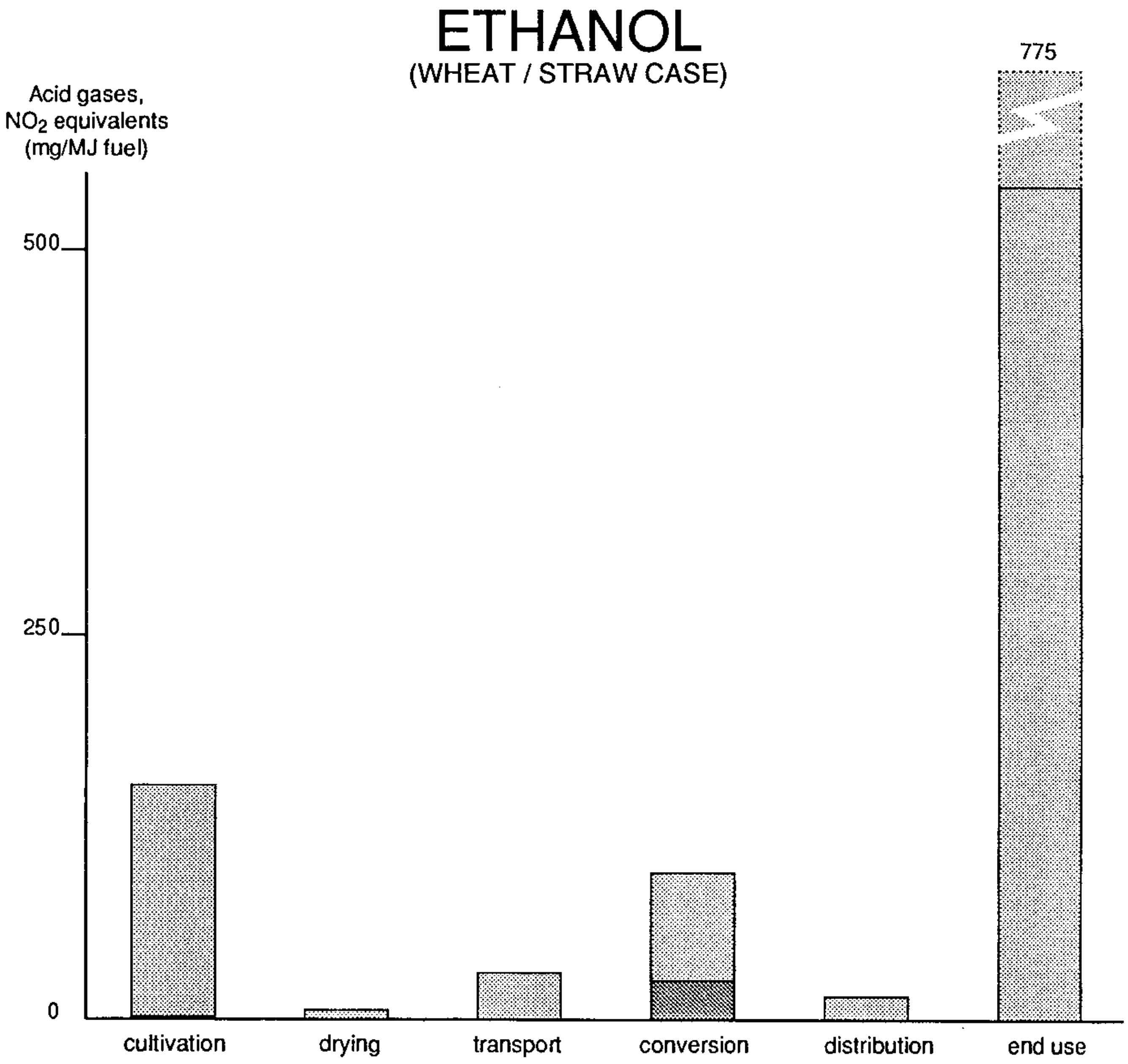

Figure 4.16 Release of acid gases in the fuel chain wheat growing to ethanol use in heavy duty diesel bus engine.

▒ NOx ░ range (for any shading)

▩ SOx

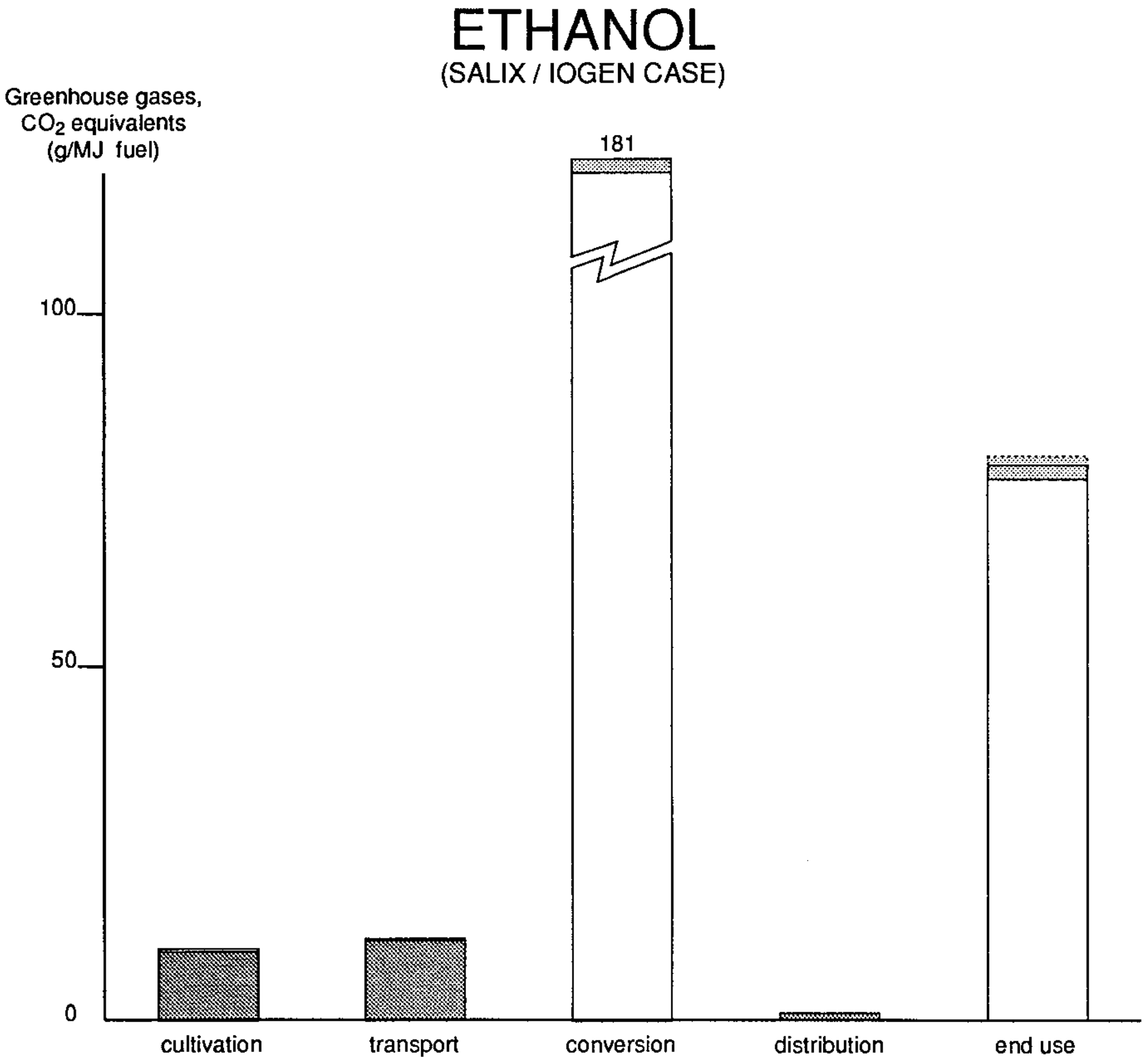

Figure 4.17 Release of greenhouse gases in the fuel chain Salix growing to ethanol use in heavy duty diesel bus engine (biomass based CO_2 included).

▩ fossil CO_2 ░ range (for any shading)

☐ renewable CO_2

▒ other greenhouse gases (methane, N_2O, NOx, other HC)

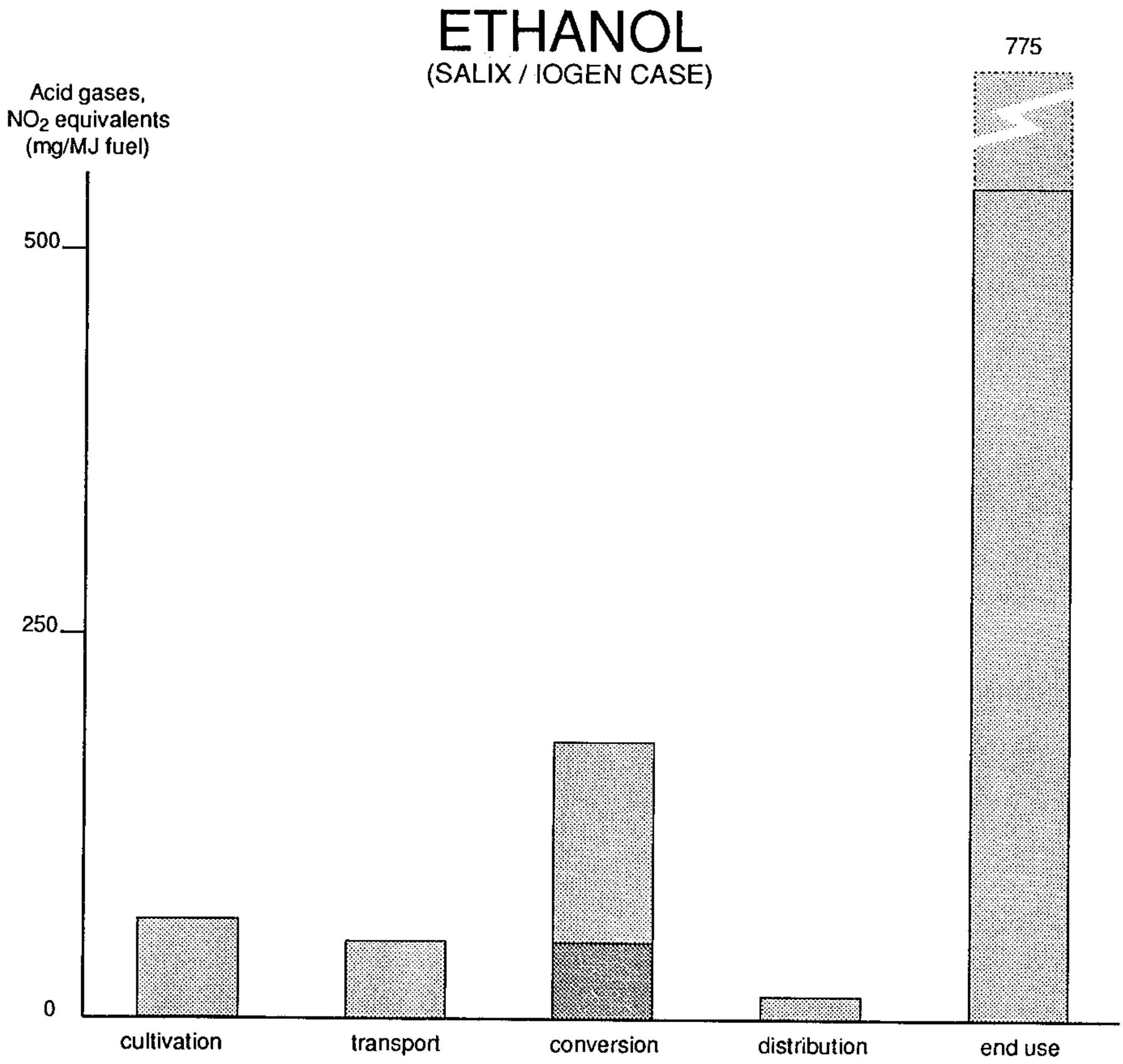

Figure 4.18 Release of acid gases in the fuel chain Salix growing to ethanol use in heavy duty diesel bus engine.

▨ NOx ░ range (for any shading)

▩ SOx

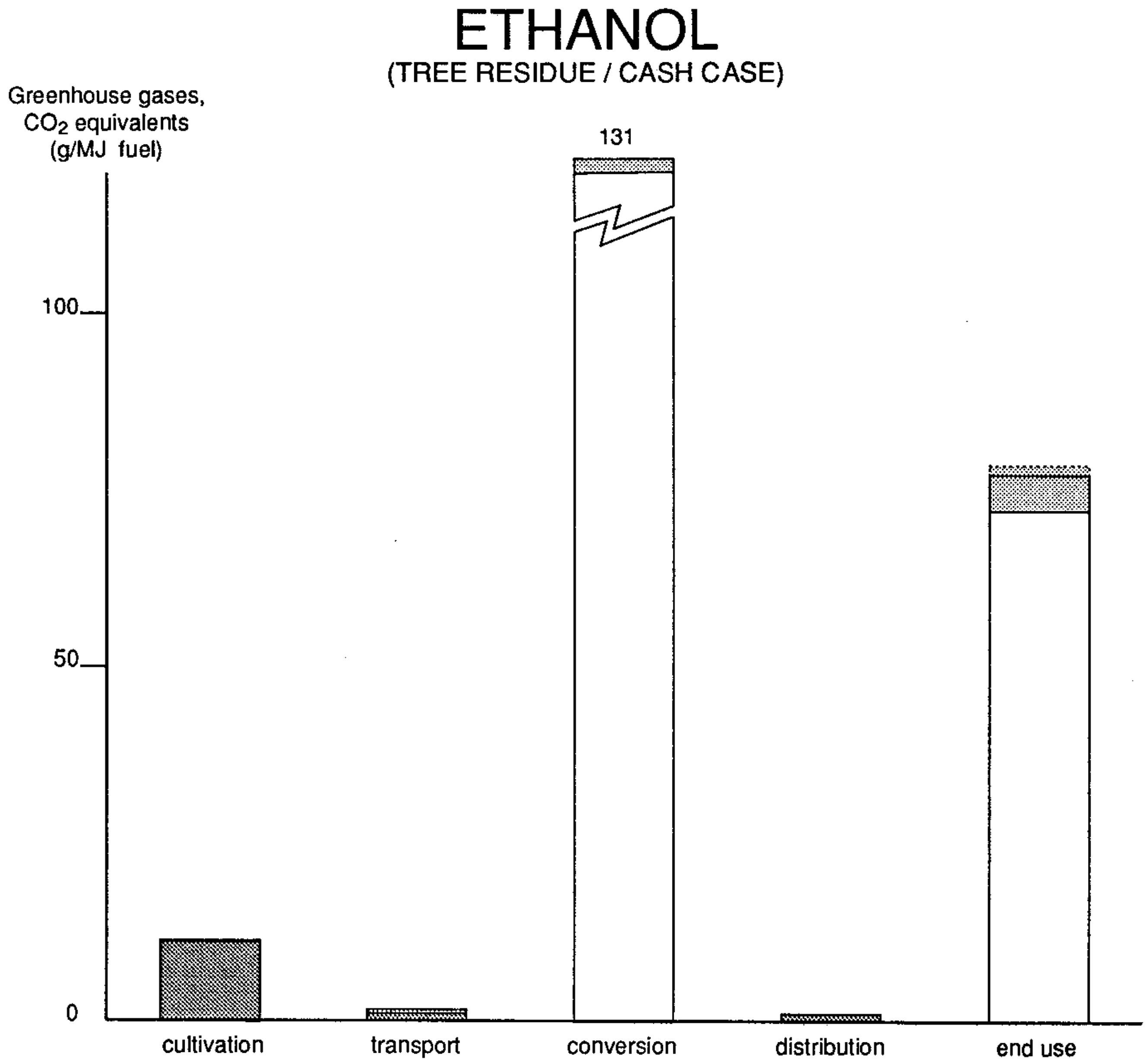

Figure 4.19 Release of greenhouse gases in the fuel chain silviculture growing to ethanol use in heavy duty diesel bus engine (biomass based CO_2 included).

▩ fossil CO_2 ░ range (for any shading)

☐ renewable CO_2

▨ other greenhouse gases (methane, N_2O, NOx, other HC)

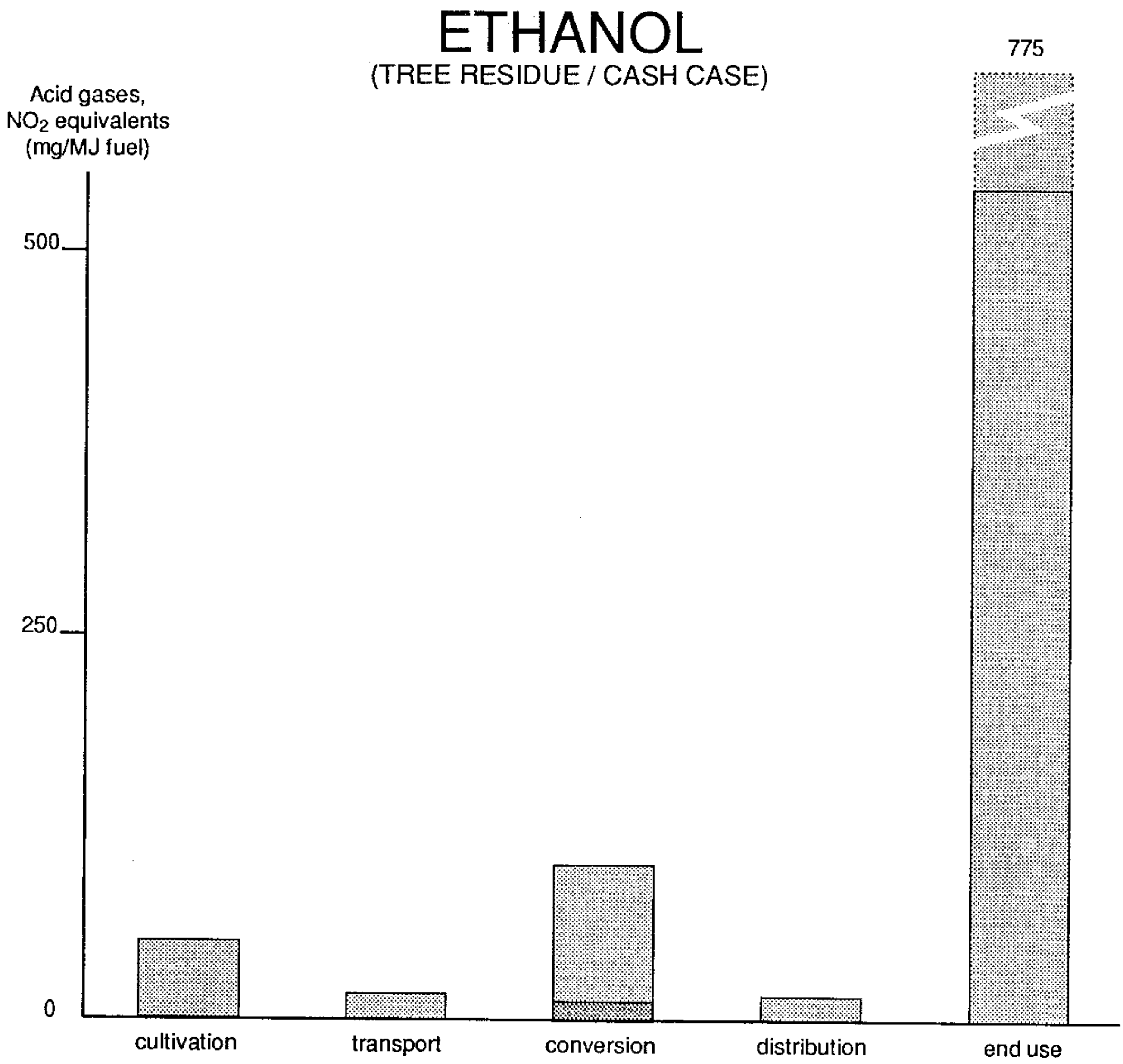

Figure 4.20 Release of acid gases in the fuel chain silviculture to ethanol use in heavy duty diesel bus engine.

▨ NOx ⬚ range (for any shading)

▩ SOx

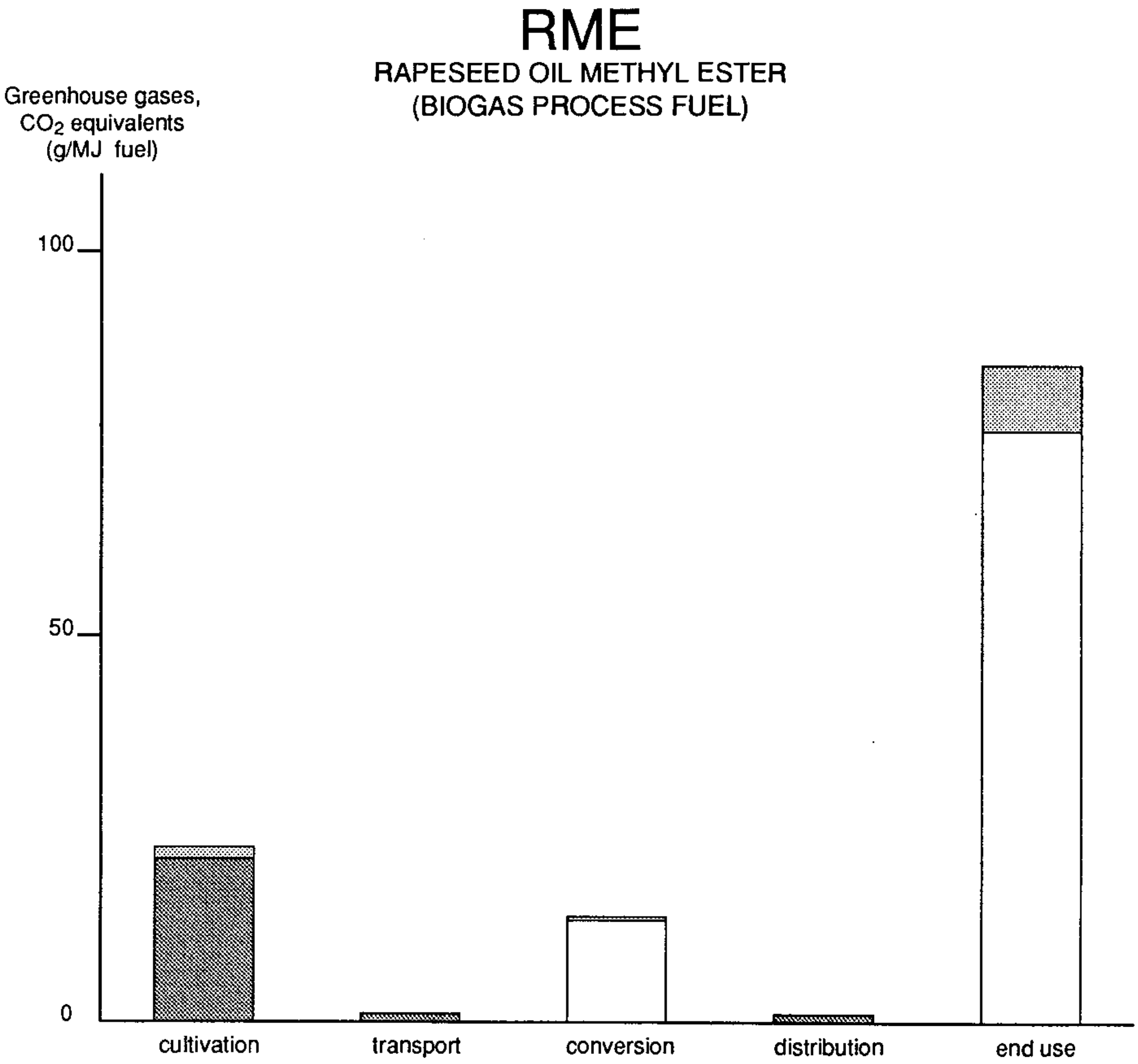

Figure 4.21 Release of greenhouse gases in the fuel chain rape growing to RME use in heavy duty diesel bus engine (biomass based CO_2 included).

▨ fossil CO_2

□ renewable CO_2

░ other greenhouse gases (methane, N_2O, NOx, other HC)

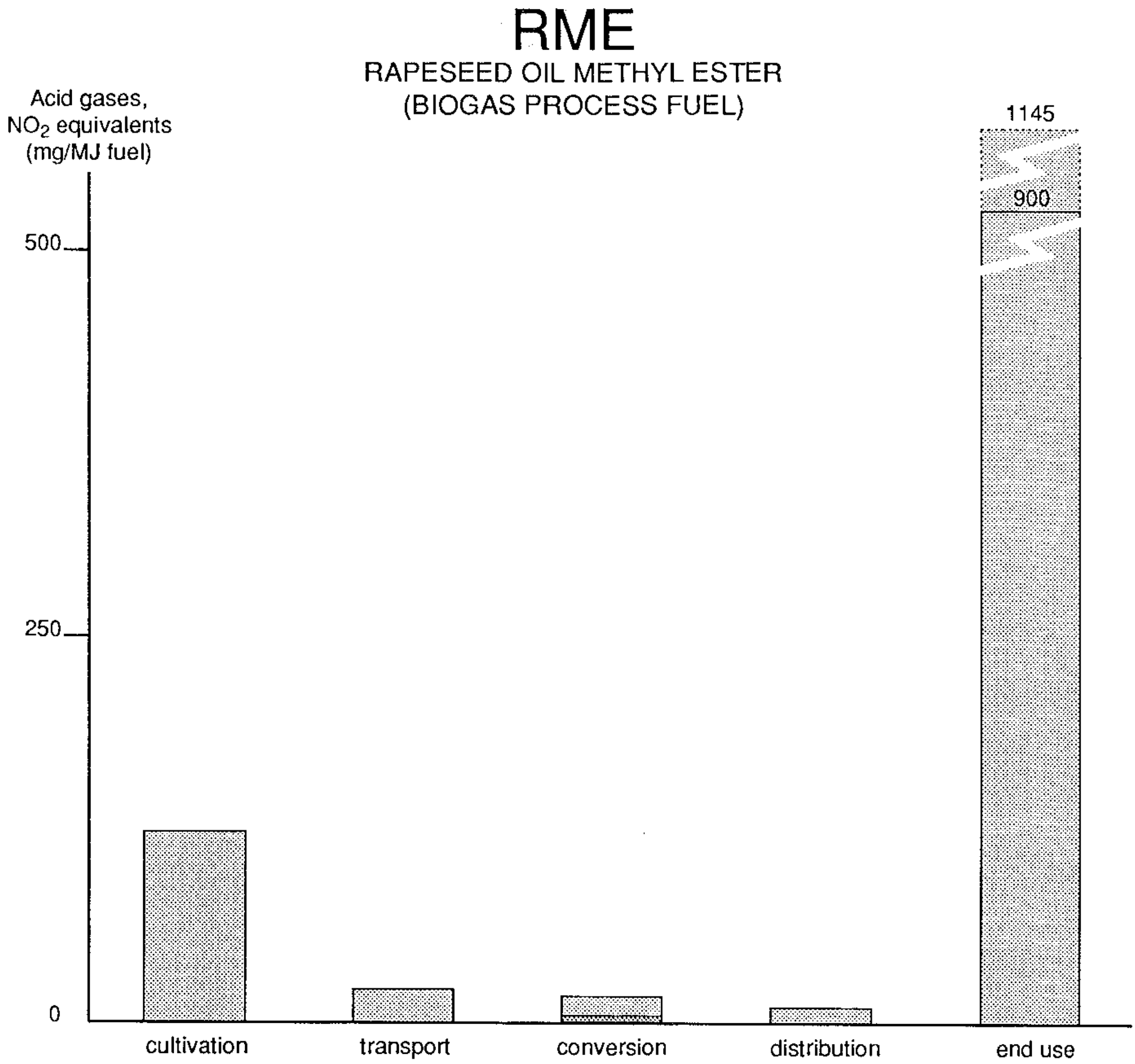

Figure 4.22 Release of acid gases in the fuel chain rape growing to RME use in heavy duty diesel bus engine.

▨ NOx ⬚ range (for any shading)

▩ SOx

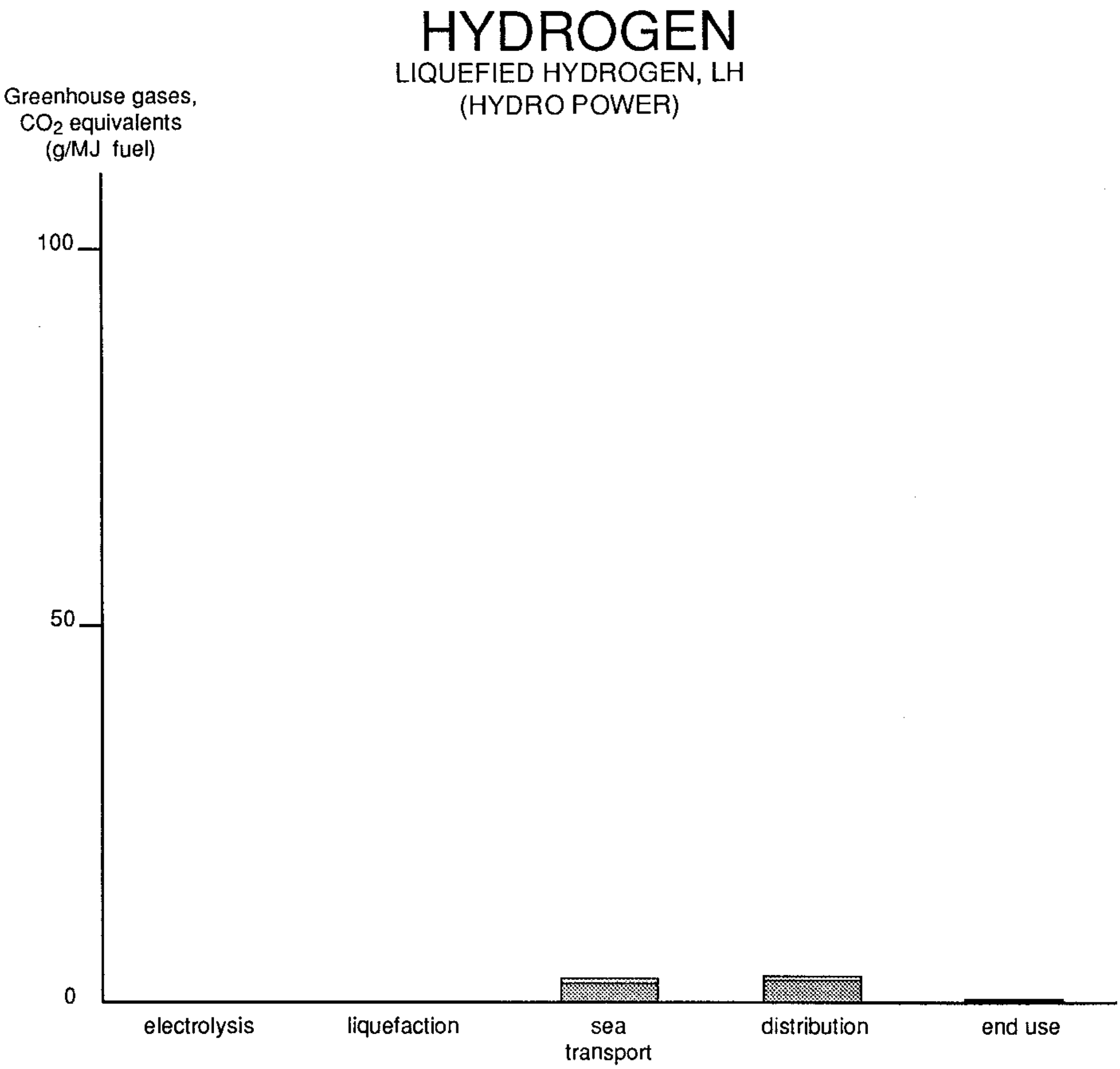

Figure 4.23 Release of greenhouse gases in the fuel chain water to hydrogen (LH) use in passenger car (PC) otto engine.

▩ fossil CO_2

☐ renewable CO_2

▨ other greenhouse gases (methane, N_2O, NOx, other HC)

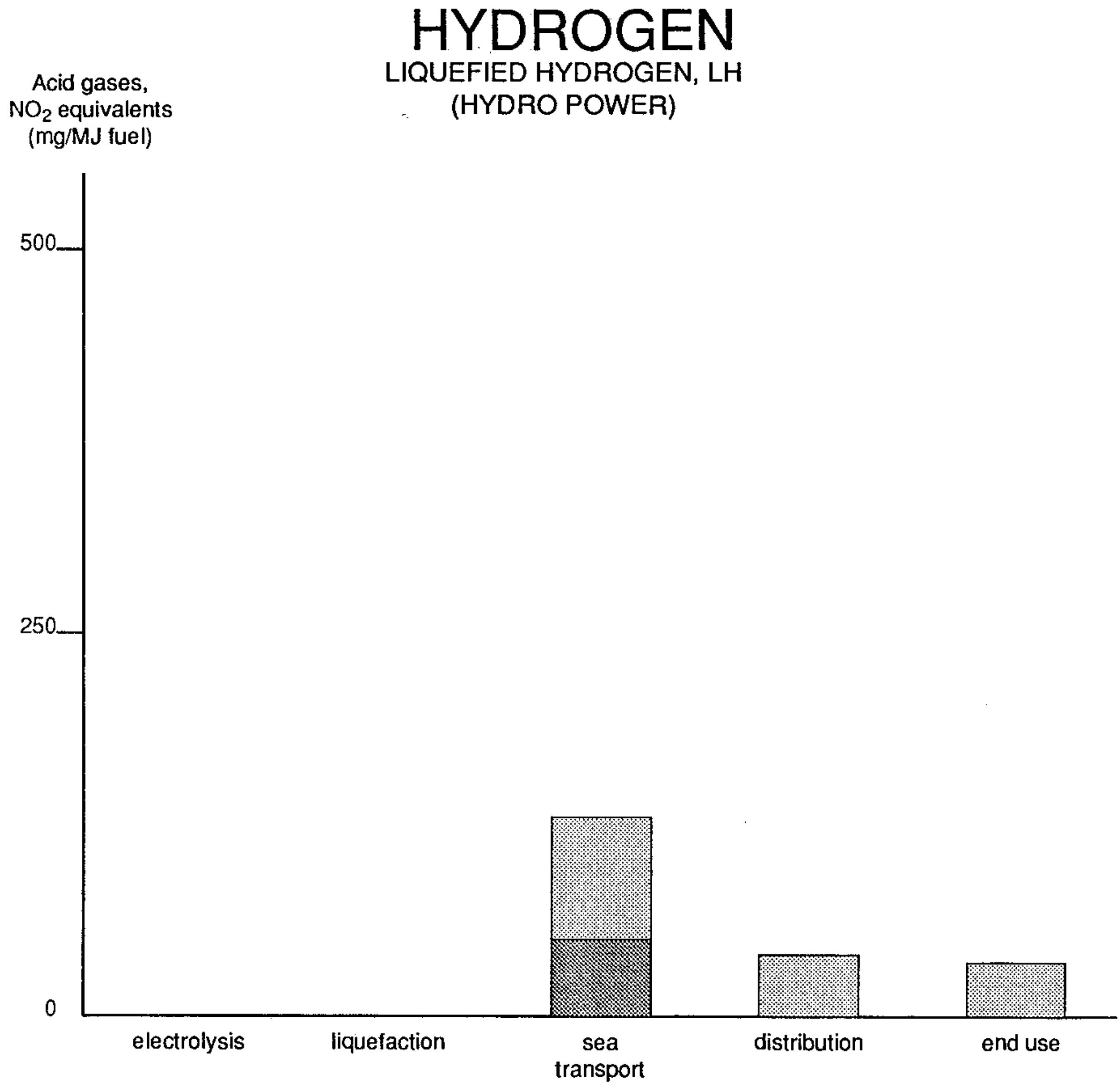

Figure 4.24 Release of acid gases in the fuel chain water to hydrogen (LH) use in passenger car (PC) otto engine.

▨ NOx

▩ SOx

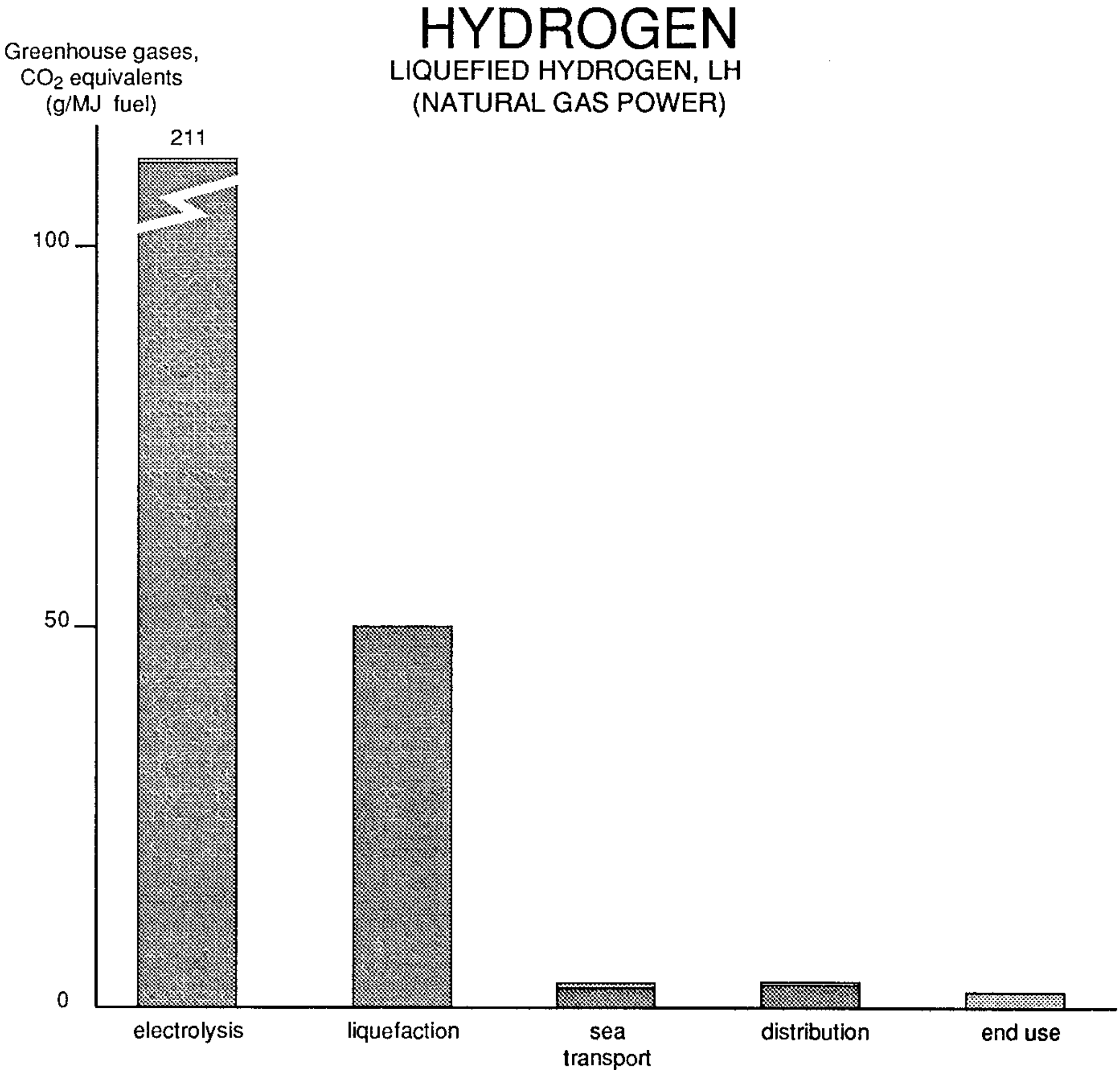

Figure 4.25 Release of greenhouse gases in the fuel chain water to hydrogen (LH) use in passenger car (PC) otto engine.

▨ fossil CO_2

☐ renewable CO_2

░ other greenhouse gases (methane, N_2O, NOx, other HC)

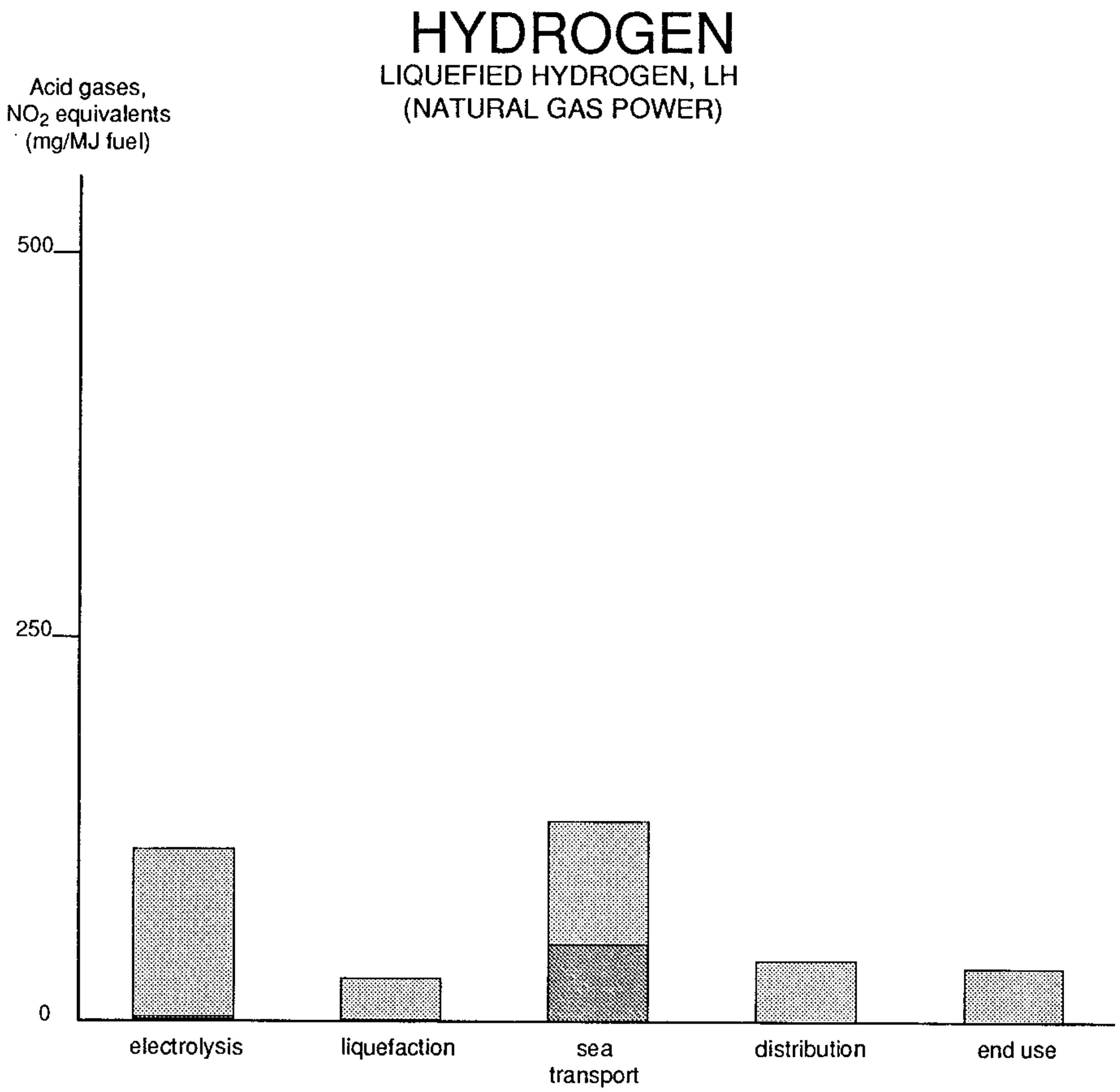

Figure 4.26 Release of acid gases in the fuel chain water to hydrogen (LH) use in passenger car (PC) otto engine.

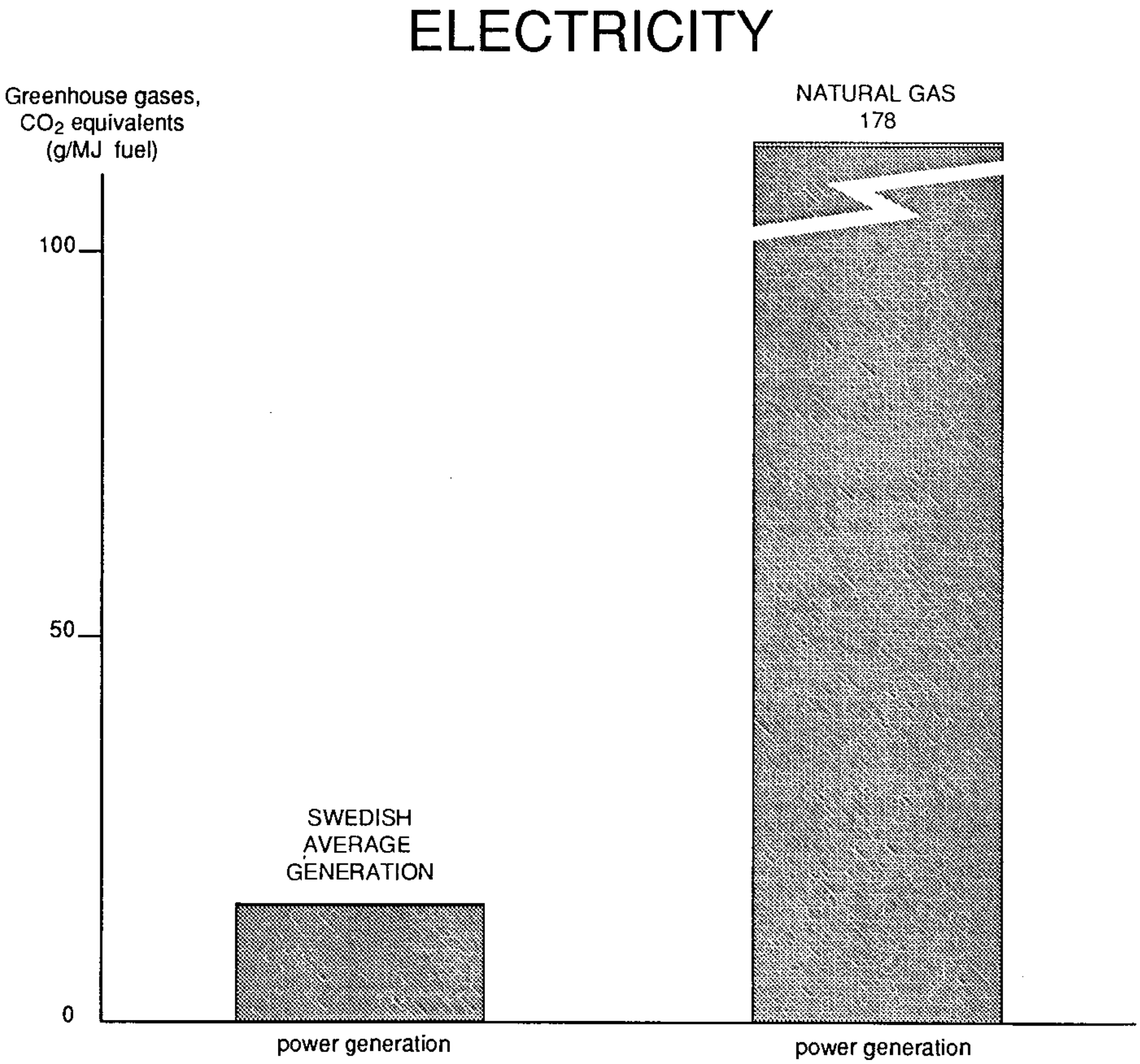

Figure 4.27 Release of greenhouse gases in the fuel chain primary energy to electricity use in electric motor.

▩ fossil CO_2

☐ renewable CO_2

▒ other greenhouse gases (methane, N_2O, NOx, other HC)

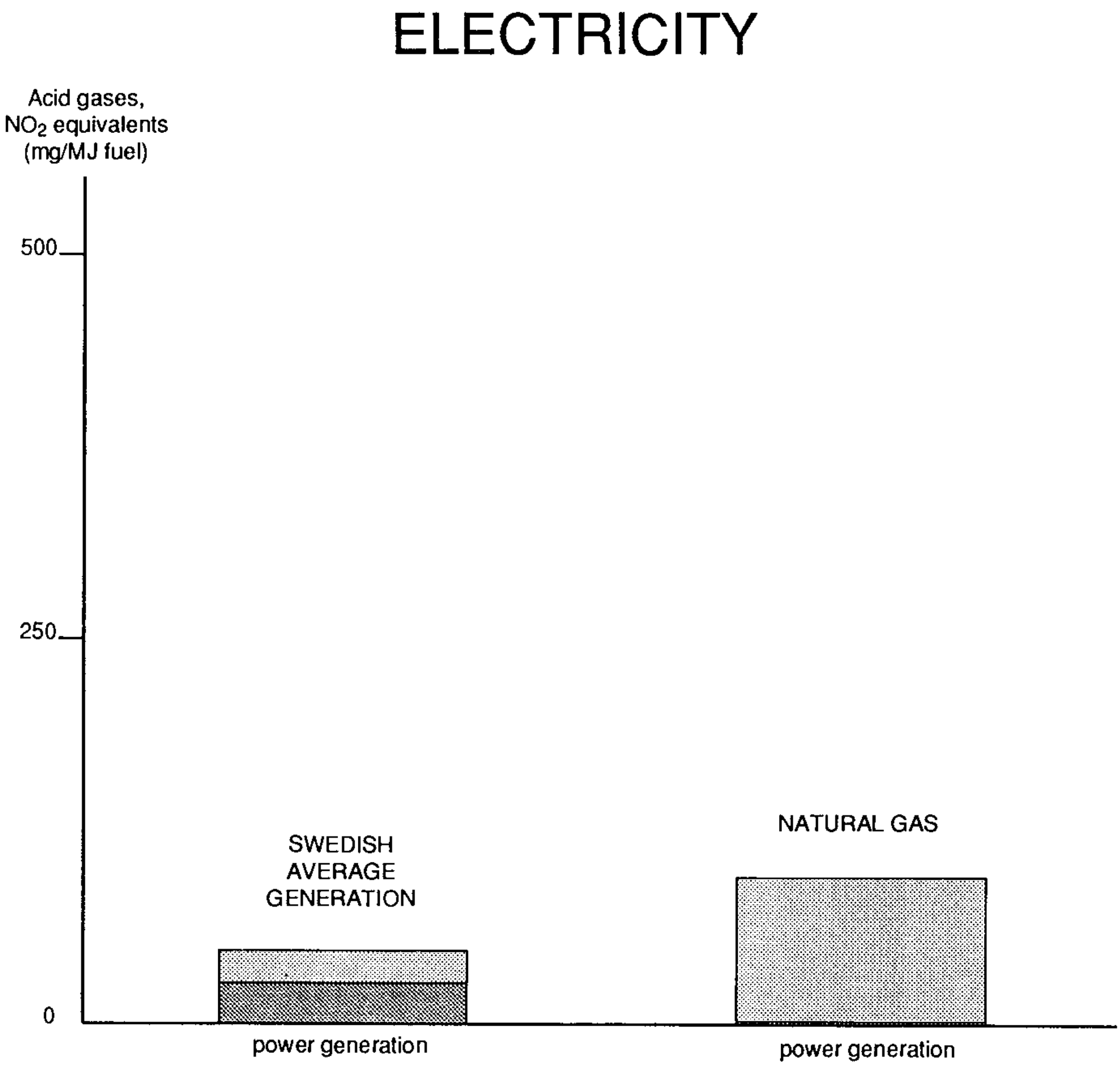

Figure 4.28 Release of acid gases in the fuel chain primary energy to electricity use in electric motor.

░ NOx

▓ SOx

5. COMPARISON OF FUELS

A complete comparison between motor fuels cannot be made without due consideration of the emission at the end-use of the vehicle and how the fuel affects the emission from the vehicle. Some fuels change the weight of the vehicle both by changing the weight of the fuel itself for equal driving range and by changing the driveline and the weight of the vehicle. Moreover, the final comparison should be made on a basis of equal useful transport work.

The comparisons made here are based on the data from the use of the fuels in heavy duty-engines in urban buses. Alternative fuels have some weight penalty because of a heavier fuel/tank system for equal driving range. For equal transport capacity, 2-5 % more buses would be required. Increased fuel consumption because of the heavier weight is of importance only for CNG-fueled buses, about 1.5 % at average payload, and for electricity fueled vehicles. Otherwise this disadvantage is disregarded.

The impacts of polluted air and deposits from polluted air on the ground and in water must be seen from several aspects, which cannot be added together to make a single total. The impacts can be distinguished as follows:

** acidifying, mainly by sulfur- and nitrogen oxides, with nitrogen overfertilization in parallel,

** oxidant forming (ozone, peroxy-compounds) by volatile organic compounds and nitrogen oxides,

** acute health damaging (bronchitis, asthma, other respiratory diseases, heart diseases), particularly to sensitive persons, by carbon monoxide, sulfur dioxide, nitrogen dioxide, ozone, soot and particles, for which standards or guidelines for concentrations in air have been listed by WHO or national agencies,

** allergy developing by yet not well known substances at low levels of exposure over long periods,

** carcinogenic due to low-level exposure over long periods to genotoxic substances (or metabolites) such as gaseous olefines, benzene, aldehydes, polycyclic aromatic compounds (often carried on submicron particles), and possibly nitrogen dioxide,

** greenhouse enhancing by carbon dioxide, methane, dinitrogen oxide, ozone, water vapor, CFC's, and, mainly indirectly, also carbon monoxide, other hydrocarbons and organic compounds, and nitrogen oxides.

5.1 Energy and emission comparisons

Based on the tables in chapter 3 and 4, the Figures 5.1-5.3 and the Tables 5.1-5.6 show comparisons between the motor fuels from the various aspects mentioned above. The following observations from the comparisons can be made.

The energy turnover, per energy unit in the tank, is much higher (up to about triple) in the biomass-based system than in the fossil oil and natural gas based systems (see Figure 5.1 and Table 5.1) because of the higher energy input to produce and convert the biomass. Energy for end use as motor fuel is about 30-50 % of the energy turnover in the bio-methanol and ethanol chains compared to 83-88 % for the oil-based fuels. Electricity as a motor fuel is somewhat special since at end use it is converted to transport work with an extraordinarily high efficiency (85 %).

The total energy turnover related to the transport work achieved (per vehicle-km) gives a more direct perspective of the energy required to perform a specific amount of transport work. This perspective is presented for the three model vehicles and for the relevant fuels in Figures 5.1a - c. In Table 5.1 the transport work achieved at end use relative to the total energy input in the whole chain is presented (in %) for passenger car and urban bus operation. In addition to the percentage of transport work achieved, relative figures for the various fuels are presented for the two vehicle types using gasoline as reference fuel for the passenger car and urban diesel oil for the bus. The figures are presented in % (round figures) of total energy input and in relation to the total resource use (two significant figures when larger than 1) for the obvious reference fuel for the two vehicle types. The ethanol fueled PC is considered, in contradiction to what is told generally for ethanol use in PCs in section 3.5, to use neat ethanol with the same efficiency as for the methanol fueled one. Hydrogen, although clean, is obviously the energy waster of the fuels studied.

Table 5.1 ENERGY EFFICIENCY - transport work at end use in relation to total energy input in the whole chain.

Fuel	**Transport work/total energy input**			
	Passenger Car		Urban Bus	
Electricity (Swedish average gen.)	50%	3.2	50%	1.5
Urban Diesel Oil	-	-	30%	1
Propane (refinery)	20%	1.1	30%	0.9
Natural Gas	20%	1.2	30%	0.9
Electricity (natural gas; condensing plant)	30%	1.8	30%	0.9
Methanol (natural gas)	15%	0.9	25%	0.8
RME (biogas fuel)	-	-	25%	0.8
RME (fossil fuel)	-	-	25%	0.8
Gasoline	15%	1	-	-
Biogas (fossil process fuel)	10%	0.8	20%	0.6
Biogas (raw biogas process fuel)	10%	0.7	15%	0.6
Methanol (tree residues)	10%	0.6	15%	0.5
Methanol (energy forest)	10%	0.6	15%	0.5
Ethanol (tree residues; CASH)	10%	0.5	15%	0.5
Ethanol (wheat; straw)	10%	0.5	15%	0.5
Ethanol (wheat; fossil fuel)	10%	0.6	15%	0.5
Ethanol (energy forest; Iogen)	5%	0.4	10%	0.4
Hydrogen	3-6%	0.2-0.4	-	-

The consumption of fossil resources is, however, considerably lower (Figure 5.1) for the biomass-based fuels (provided that biomass is used as the process fuel in the ethanol case; if not, it is only slightly better than for diesel oil). Fossil resource consumption is only about 10 % or less of total energy resource utilization with the renewable energy based fuels (biogas, methanol, ethanol, hydrogen, electricity) compared to 100 % with gasoline and diesel oil. In Table 5.2 the transport work achieved relative to the fossil energy use is compiled for passenger car and urban bus use respectively. The figures are presented in % (round figures) of fossil energy input and in relation to the fossil resource use (two significant figures when >1) for the obvious reference fuel for the two vehicle types. The ethanol fueled PC is considered, in contradiction to what is told generally for ethanol use in PCs in section 3.5, to use neat ethanol with the same efficiency as for the methanol fueled one.

Table 5.2 ENERGY EFFICIENCY - transport work at end use in relation to fossil energy in put in the whole chain.

Fuel	**Transport work/fossil energy input**			
	Passenger Car		Urban Bus	
Biogas (raw biogas process fuel)	no net fossil fuel need			
Electricity (Swedish average gen.)	400%	29	400%	14
Ethanol (tree residues; CASH)	250%	17	400%	14
Methanol (tree residues)	200%	12	300%	10
Hydrogen (hydro power)	125%	8.3	-	-
Methanol (energy forest)	100%	7.5	200%	6.3
Ethanol (energy forest; Iogen)	100%	6.1	150%	5.2
Ethanol (wheat; straw)	100%	5.6	150%	4.8
Biogas (fossil process fuel)	65%	4.4	100%	3.5
RME (biogas fuel)	-	-	100%	3.4
RME (fossil fuel)	-	-	80%	2.5
Ethanol (wheat; fossil fuel)	20%	1.2	30%	1.1
Urban Diesel Oil	-	-	30%	1
Propane (refinery)	20%	1.1	30%	0.9
Natural Gas	20%	1.2	30%	0.9
Electricity (natural gas; condensing plant)	30%	1.8	30%	0.9
Gasoline	15%	1	-	-
Methanol (natural gas)	15%	0.9	25%	0.8
Hydrogen (natural gas)	5%	0.3	-	-

The input of fossil energy in the bio-fuel chains is multiplied by the bio-synthesis to give several times more motor fuel energy. Table 5.3, below, shows this "amplification factor" for the cases studied. In theory the bio-chains may consume nearly no net fossil resources at all, if fertilizers are also produced from biomass feedstock or credit for by-product fertilizers can be obtained. This is indicated for the lucerne-to-biogas chain because the crop is able to bind nitrogen from the air. Extensively grown forest biomass as feedstock for methanol and ethanol yield very large factors because of low energy usage (fertilizers, motor fuel) in the silviculture.

Table 5.3 Amplification factors (ratio motor fuel produced over fossil energy use in the whole chain).

Fuel	Gaso- line	Urban diesel	Pro- pane	CNG	Bio- gas	Methanol		Ethanol	RME	H_2	El
Feed- stock	crude	crude	crude	NG	luc- erne	NG	tree resid.	tree resid.	rape	wa- ter	hyd- ro
Process fuel	---------	fossil	-----------				-"-	-"-	bio- mass	hyd- rop.	ren +fo
Ampl. factor	0.83	0.88	0.86	0.88	3.3	0.69	9	12	3	7	5

(C)NG = (Compressed) Natural Gas RME = Rapeseed Oil Methyl Ester
H_2 = Hydrogen El = Electricity
The RME case is not quite comparable to the others (see page 39).

The contribution to the emission of greenhouse gases (Figure 5.2 and Table 5.4) is for the bio-fuel chains less, often considerably less, than half of these emissions from the oil based fuel chains. The greenhouse effect may in fact be somewhat lower still because biomass chains as energy crop cultivations, particularly energy forests, will serve as a carbon dioxide sink by increased accumulation of carbon in root systems and in the soil. This is not accounted for in the data given as they only comprise the biomass harvested. The end use dominates the greenhouse gas emissions for oil and natural gas based fuel chains but in the bio-chains the biomass production gives the largest contribution.

Table 5.4 GREENHOUSE GASES in the whole chain including end use CO_2 equivalents (g/vkm and relative).

	Passenger Car		Urban Bus	
Electricity (Swedish average gen.)	10	0.03	90	0.06
Hydrogen (hydro power)	20	0.06	-	-
Methanol (energy forest)	70	0.20	300	0.19
Ethanol (tree residues; CASH)	-	-	350	0.22
Ethanol (energy forest; logen)	-	-	500	0.31
Biogas (lucerne)	90	0.25	500	0.31
RME	-	-	550	0.34
Ethanol (wheat; straw)	-	-	700	0.43
Electricity (natural gas; condensing plant)	120	0.3	1100	0.69
Natural Gas (compressed)	230	0.7	1400	0.88
Propane	300	0.9	1500	0.94
Methanol (natural gas feedstock)	300	0.9	1500	0.94
Urban Diesel Oil	-	-	1600	1
Gasoline	350	1	-	-

Methanol from natural gas yields about 10 % less greenhouse gases and natural gas about 25 % less than diesel oil, but the latter figure is somewhat counteracted by lower engine efficiency with gas. Hydrogen and electricity from hydro power and similar origins yield, of course, the lowest greenhouse gas releases of all fuel chains studied. Methanol and ethanol from ligno-cellulosic feedstocks are next, with nearly 80 % less than the oil based fuels. Electricity from natural gas gives only a moderate advantage over the conventional fuels in heavy vehicles (30 % less) but a considerable one in passenger cars (70 % less).

The acidification potential (Figure 5.3 and Table 5.5) is highly dominated by the emissions of nitrogen oxides and the emissions at the end use. Diesel oil and vegetable oil show the highest figures, and the lowest figures are obtained with fuel/engine-combinations which can use catalytic NOx-reduction. The bio-chains give rather high contributions to NOx-emissions at the biomass production and conversion stages. Electricity, also when produced from natural gas, may have the best potential to reduce acidifying emissions.

Table 5.5 ACID GASES (SOx and NOx) in the whole chain including end use

Fuel	**NO_2 equivalents** (g/vkm and relative)			
	Passenger Car		Urban Bus	
Electricity (Swedish average gen.)	0.03	0.05	0.3	0.02
Electricity (natural gas; condensing plant)	0.06	0.1	0.6	0.04
Hydrogen (hydro power)	0.6	1	-	-
Gasoline	0.6	1	-	-
Propane (field)	0.7	1.2	5	0.3
Natural Gas (compressed)	0.5	0.8	6	0.35
Propane (refinery)	0.9	1.5	6	0.35
Biogas	0.8	1.3	8	0.5
Methanol (tree residues)	-		10	0.6
Methanol (energy forest)	0.8	1.3	10	0.6
Methanol (natural gas feedstock)	1.0	1.7	11	0.65
Ethanol (tree residues; CASH)	-	-	12-16	0.7-0.9
Ethanol (energy forest; Iogen)	-	-	14-18	0.8-1.1
Ethanol (wheat; straw)	-	-	14-18	0.8-1.1
Urban Diesel Oil	-	-	15-19	**0.9-1.1**
RME	-	-	17-22	1 - 1.3

The picture of emissions of oxidant forming precursors is less clear due to lack of data in several steps. It seems likely that the end use in gasoline and diesel oil engines are the main sources although the emissions can be reduced to a low level for both fuels by efficient catalysts. The lower reactivity of unburned methane and alcohols (section 2.2.1 and .2) may give these fuels an edge over the oil based fuels, which is indicated in many air quality modeling studies. The unburned hydrocarbons of the oil based fuels are mainly reactive olefins. Methane and methanol yield very low quantities of olefins. The higher emissions of aldehydes (and alkyl nitrites) from alcohols may at least partly outweigh this advantage. The successful use of catalytic systems, still under development for diesel engines, will be decisive for a final judgement.

Cancer risks because of emissions of air toxics (Table 5.6) such as benzene and alkenes will be reduced and PAC and particles will be greatly reduced by the use of gaseous and alcohol fuels, although PAC-emissions at the conversion plants, where biomass is burned in boilers, is an unknown factor. The absence of fuel-derived benzene from methane, propane and alcohols will lower cancer risks but is counteracted by the higher aldehyde emissions. Olefin (ethene) emissions are as mentioned very low for methane and methanol fuels and a reason for lower risks with these fuels. The role of the higher emissions of nitrogen dioxide and alkyl nitrites is not yet finally evaluated. The effects of the latter are ruled to be small because of the short lifetime of the nitrites in the atmosphere. Again, final judgements have to await the development of efficient catalyst systems and clarifications of exposures.

Table 5.6 AIR TOXICS, qualitative comparison for the whole chain

Fuel	Benzene	Alkenes	Aldehydes	PAC	Particles
Electricity (excl coal and oil based cond.)	0	0	0	0	0
Methane	0	Δ	Δ	0	0
Methanol	0	Δ	++	0	0
Ethanol	0	+	++	0	0
Gasoline (reformulated)	++	++	+	+	Δ
Diesel Oil (urban)	+	++	+	++	++

0 = no or negligibly small
Δ = small
\+ = moderate
++ = somewhat larger; levels of concern

5.2 Motor fuels in the total view on energy and environment

The effects discussed in section 5.1 on the total change of the effects via polluted air will, of course, depend on the share from the transport sector, on the penetration of new fuels on the market and on the share of man-made emissions in relation to natural emissions /55/.

Man-made CO_2 emissions correspond to about 6 Gt/yr carbon and the transport sector accounts for about 20 %. The emissions are only a few percent of the total exchange of CO_2 between the atmosphere and land and sea. Still the CO_2 concentration in the atmosphere is now rapidly increasing because of the inertia of the exchange mechanisms. The only effective contributions to halting CO_2 releases from the transport sector are improved efficiency in the use of motor fuels in transport and greatly increased use of biomass feedstocks. The importance of lowering emissions in the entire fuel chain and of other greenhouse gases by improved control systems is, however, clearly demonstrated above.

Emission of sulfur dioxide from man-made sources is estimated to be about equal to that from natural sources (volcanoes, decay of organic matter, natural fires) and has its main origin in combustion of oil and coal by utilities. The modern motor fuels are a very minor contributor to emissions of sulfur dioxide provided that effi-cient emission controls are applied earlier in the fuel chain.

About one third of the global emissions of carbon monoxide originate from man-made activities, and road traffic is a major contributor.Its emissions occur mainly in urban areas where concentrations of people live. The present downward emission trend is largely due to the introduction of emission controls on vehicles.

Particulate matter (PM) of man-made origin (combustion of fuels) is often toxic, in contrast to natural dust, because of its content of PAC (polycyclic aromatic compounds) and other substances, and therefore it is of greater concern to human health (cancer). Wood combustion, particularly in small furnaces, can be a major source of PM with mutagenic response. An observed reduction in PM emissions is partly due to industrial installations of dust removal equipment, but it is partly offset by increased emissions from the expanded use of diesel oil powered vehicles. This is particularly true for the finest, sub-micron, inhalable particles and these emissions occur mainly in urban areas. The chemically simple alternative motor fuels offer the possibility of a large reduction, if not virtual elimination of fuel related, inhalable PM.

Man-made nitrogen oxides, being or taking part in many reactions leading to harmful compounds in air, are mainly emitted as nitric oxide, NO, which in the atmosphere is oxidized to the more toxic nitrogen dioxide and to nitrous and nitric acid. The contribution from the road traffic is 50 % or more in industrialized countries. In most countries emissions are not falling but rising. Natural emissions, from the decay of organic material in soil and water and from natural fires, may be significant but they are to a large extent in the form of dinitrogen oxide, which is nonreactive in the lower atmosphere (but a greenhouse gas). Changed land use from traditional agricultural crops to short rotation energy forests is assumed not to increase nitrogen oxide emissions but rather diminish them due to less intense use of fertilizers.

Improved catalytic reduction systems offer further reduction of NOx emissions, to which the alternative fuels may contribute additionally, particularly in heavy duty diesel engines.

Volatile organic compounds (VOC) comprise a great number of compounds, some of which are highly reactive in oxidant formation and some have health implications, i.e. are toxic. At the global scale methane, the least reactive VOC, is the most abundant hydrocarbon, which is mainly produced by natural processes. Methane emissions seem, however, to be related to human activities, and the atmospheric methane content closely follows the increase in world population. The energy sector in total accounts for 10-20 % of the global emissions and the transportation sectors thus for a few percent.

Emissions of natural non-methane VOC stem mainly from coniferous and deciduous forests and wetlands and some are very reactive in oxidant formation (terpenes, isoprene). Natural emissions vary considerably between different areas and may in some be of the same magnitude as man-made VOC or higher. It seems unknown whether changed land use from agricultural crops to energy forests will influence non-methane VOC-emissions.

Up to 50 % of the emissions of man-made, non-methane VOC originate in the industrialized countries from road traffic. VOC emissions have during the last decade remained broadly stable or increased and the share emitted by road traffic is increasing (except in the U.S.). Alternative motor fuels offer the possibility of large reductions in reactive, non-methane emissions beyond what can be achieved with gasoline and diesel oil. This is valid also in connection with improved catalytic clean-up systems.

In this study we have looked into the energy utilization of each step of the various fuel chains and the adherent airborne emissions and presented figures for energy use and emissions of various components. These figures are on an absolute basis and it could be argued that they should be subtracted by the corresponding figures for the alternative use of each asset made use of, if it were not used in a fuel chain. This should, of course, be made in any actual change situation in order to enable the estimate of the net effect on energy use and airborne emissions of the change considered. Such comparisons, however, are outside the scope of the present study and would not, to the best of our judgement, have any effect on the conclusions possible to draw from it.

Local effects

Standards or guidelines for air quality concerning sulfur dioxide, nitrogen dioxide, ozone and particulate matter (especially the smallest particles) are frequently exceeded, particularly along lively trafficated roads, causing health effects and damages to plants and trees. Oxygenates and other incompletely burned fuel compounds likely contribute to the health impact.

Land use changes, especially the introduction of energy forestry based on fast-growing Eucalyptus species giving large emissions of isoprene, could also cause health effects.

Cancer incidences because of polluted urban air, to which the road traffic is the major contributor, are according to Swedish estimates, 2 cases (1 lethal) per 10,000 persons per year. This risk corresponds to the upper limit accepted for occupational radiation exposures and is thus 10 to 100 times higher than an acceptable risk for individuals among the public in urban areas.
Deposition of acid compounds cause damage to buildings and monuments, endangering our cultural heritage. Corrosion of concrete and steel structures may become a severe problem. Synergistic

effects between sulfur and nitrogen oxides increase all these types of damage.

Regional effects

Ecological effects are mostly related to the total exposures and depositions over long periods and are influenced also by pollutants transported from distant sources. The effects of nearby deposition of nitrogen oxides have been observed along lively trafficated highways. Both sulfur and nitrogen oxides and ozone disturb the photosynthesis and depositions acidify the soil and water, causing damage to forestry and fishing.

If acidification goes too far, nutrient salts will be leached out and aluminum liberated, increasing the damage. Too high deposition, above what the soil can absorb - the critical load, of nitrogen compounds will result in spills of these into the ground water and waterways, causing abnormal growth of microrganisms in the latter. Irreversible flora changes have already taken place and damage to forest and lakes is spreading, most quickly in areas with soils of low buffering capacity. The present limits to NOx emissions are not low enough to reverse this trend but only slow down the process. Techniques to meet much more string-ent emission limits are available.

Ozone levels are over wide areas high enough to cause reduced growth of agricultural crops.

Global effects

The global effects depend on releases of longlived gases to the atmosphere, affecting the radiative balance of the earth and for some gases destroying the protective stratospheric layer of ozone.

The contribution from the transport sector is mainly the releases of fossil carbon dioxide and ozone-forming gases in the troposphere, while methane and dinitrogen oxide play a minor role. The observed increases of formation of dinitrogen oxide from present exhaust catalytic systems may be outweighed by the reduced total nitrogen oxide emissions being an indirect source after deposition. Dinitrogen oxide contributes to the destruction of stratospheric ozone. Chlorine containing CFC's, used in vehicle air-conditioning systems and in the manufacture of foamed auto parts, are the most effective in this process. These uses of CFCs are now being abandoned in favor of less harmful compounds.

The transport sector is a moderate, but increasing contributor, about 20 %, to the man-made carbon dioxide emissions.

The role of alternative motor fuels

In order to deal with the local, regional and global, that is international, problems, better management of air resources is needed in world-wide cooperation /55/. For the transport sector, being international in both fuels and vehicles, this means better enforcement of existing national regulations and policies, and rigorous implementation of international agreements. It is realized that present emission standards are insufficient to reverse the trend of increasing environmental and health damages. Much more stringent standards have to be adopted and are already technically possible to implement. New toxic compounds must be controlled and regulated, for instance benzene and other genotoxics. Such a development has started in the U.S. and particularly in California.

From the data compiled in this study it seems that **alternative motor fuels** such as methane and alcohols can play a crucial role in this needed development, as they can be utilized on a very large scale. Although the data base is not yet complete, it has been shown that the use of methane and bio-alcohols will result in lower carbon dioxide and greenhouse gas releases, particularly if natural gas now flared and biogas now vented from garbage dumps and biomass feedstocks are utilized (also as process fuels).

Nitrogen oxide emissions from methane- and alcohol-fueled diesel engines can be considerably lower than from diesel oil-fueled engines.

Fuel-related genotoxic compounds of PAC-type and benzene are virtually eliminated with the use of methane and alcohols as motor fuels and gaseous olefins are much reduced.

Methane gives the lowest emissions of all health risk related compounds, whereas there is still uncertainty about the evaluation of higher aldehyde emissions and alkyl nitrite formation with alcohols.

Oxidant formation is considerably lower with the alternative motor fuels in comparison to the conventional hydrocarbon fuels.

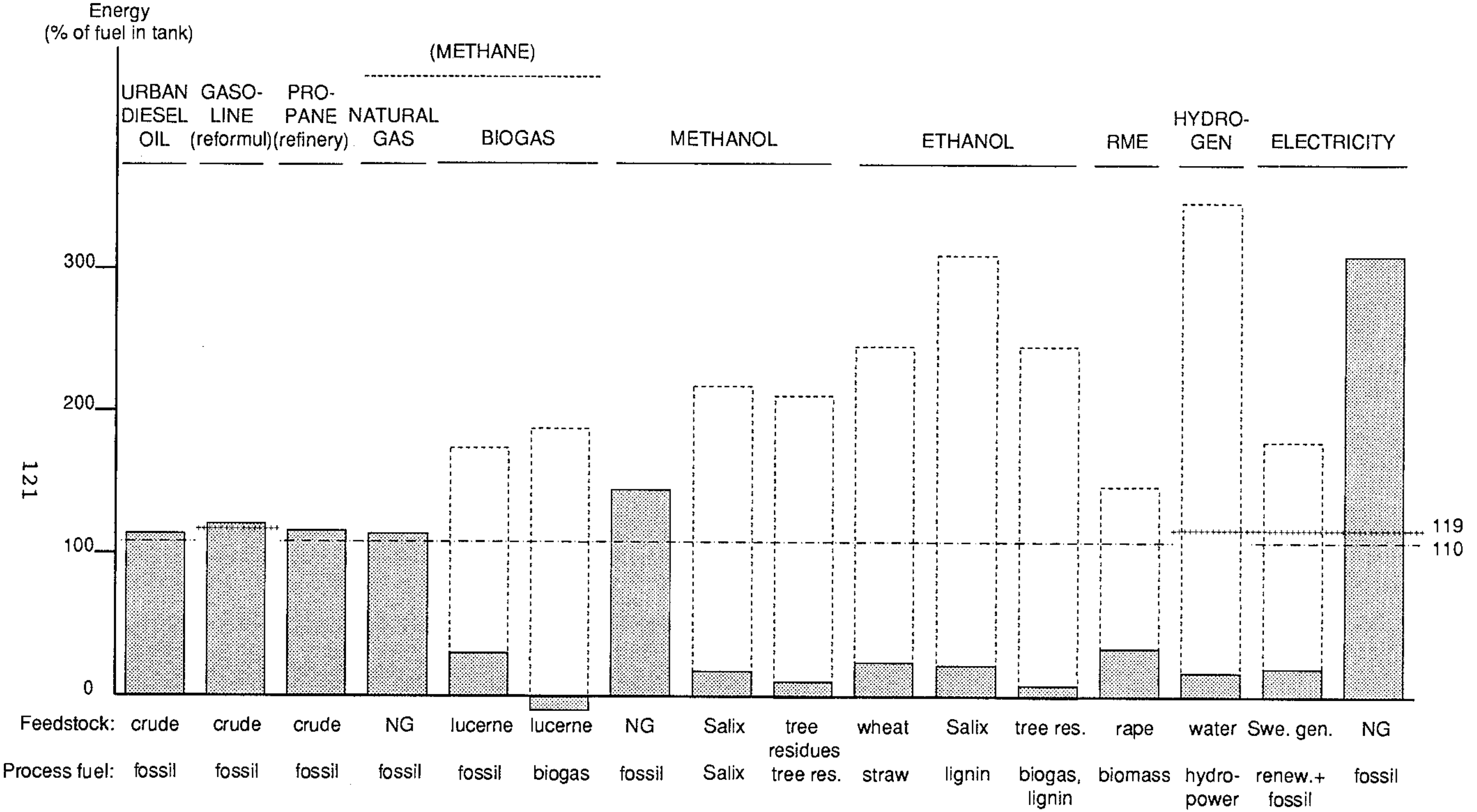

Figure 5.1 Energy resource use for fuel chains (bus diesel engine except for gasoline, hydrogen and electricity).

▨ net fossil energy resource consumption.

☐ renewable energy resource consumption.

++++++++ reference gasoline passenger car

._._.. reference diesel oil heavy duty bus

NG=Natural Gas
RME=Rapeseed Oil Methyl Ester

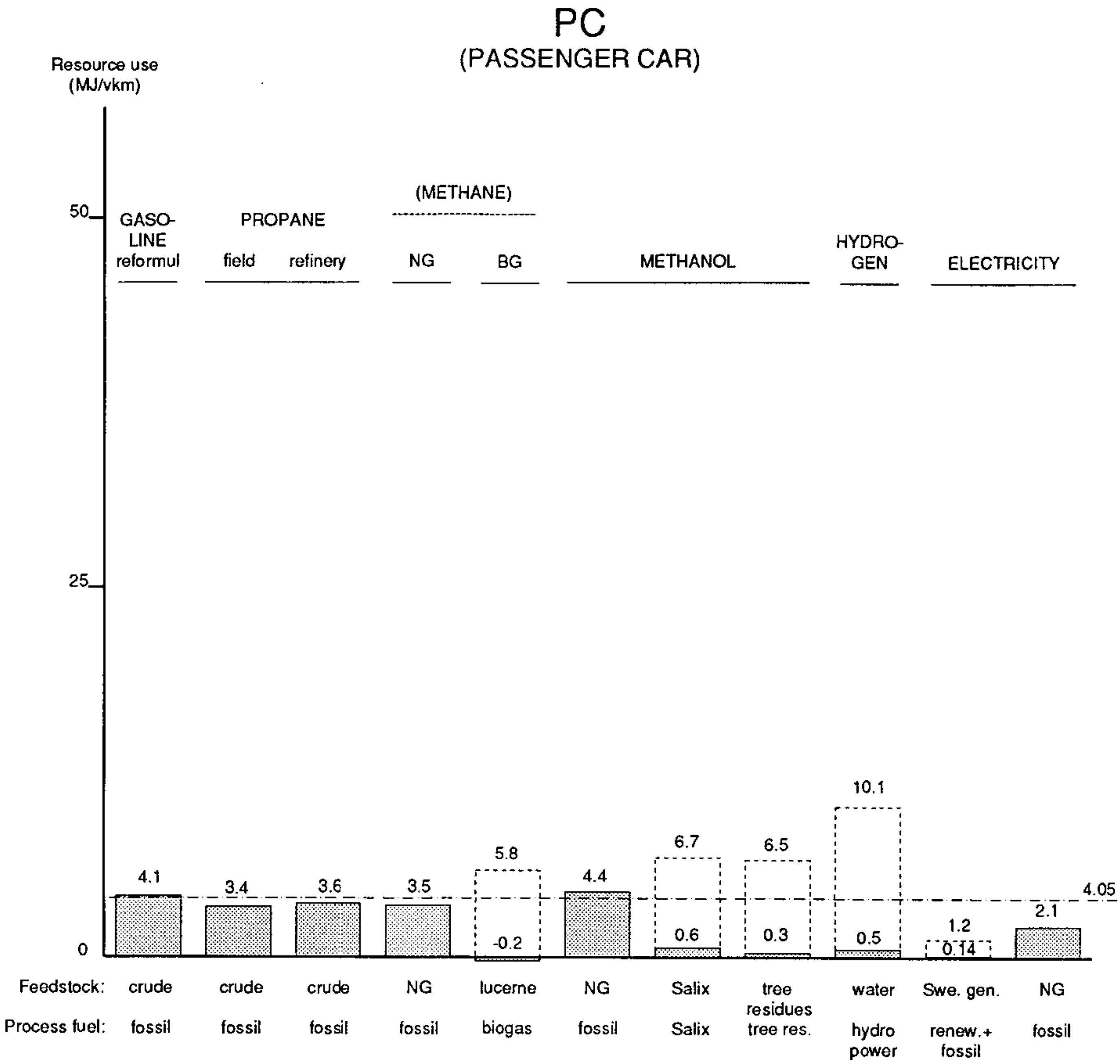

Figure 5.1a Energy resource consumption in PC model vehicle for fuel chains.

▨ net fossil energy resource consumption

⬚ renewable energy resource consumption

—·—· model vehicle/reference fuel resource consumption (standard gasoline)

NG=Natural Gas

BG=Biogas

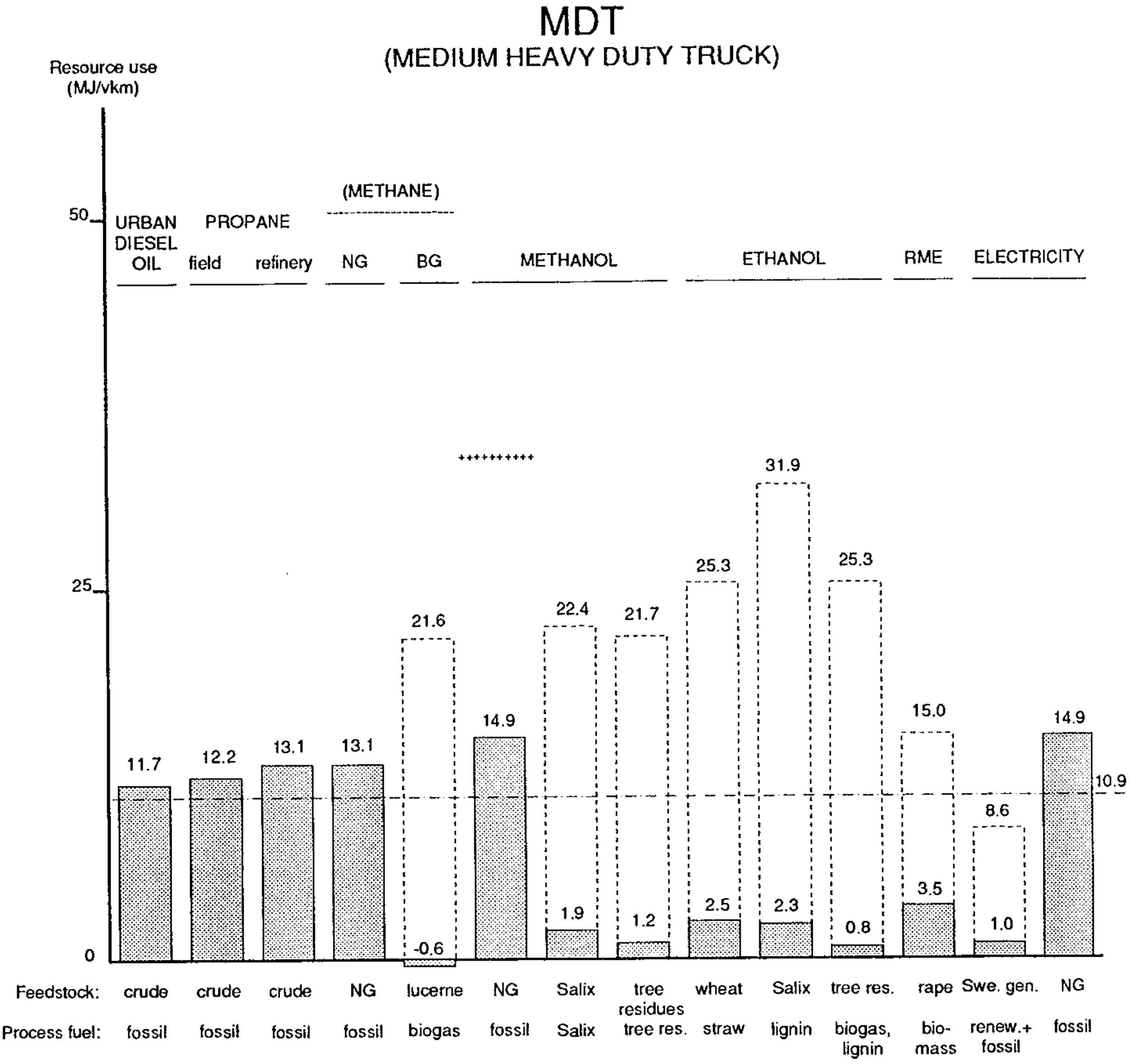

Figure 5.1b Energy resource consumption in MDT model vehicle for fuel chains.

▨ net fossil energy resource consumption

☐ renewable energy resource consumption

-·-·- model vehicle/reference fuel resource consumption (standard diesel oil)

NG=Natural Gas

BG=Biogas

RME= Rapeseed Oil Methyl Ester

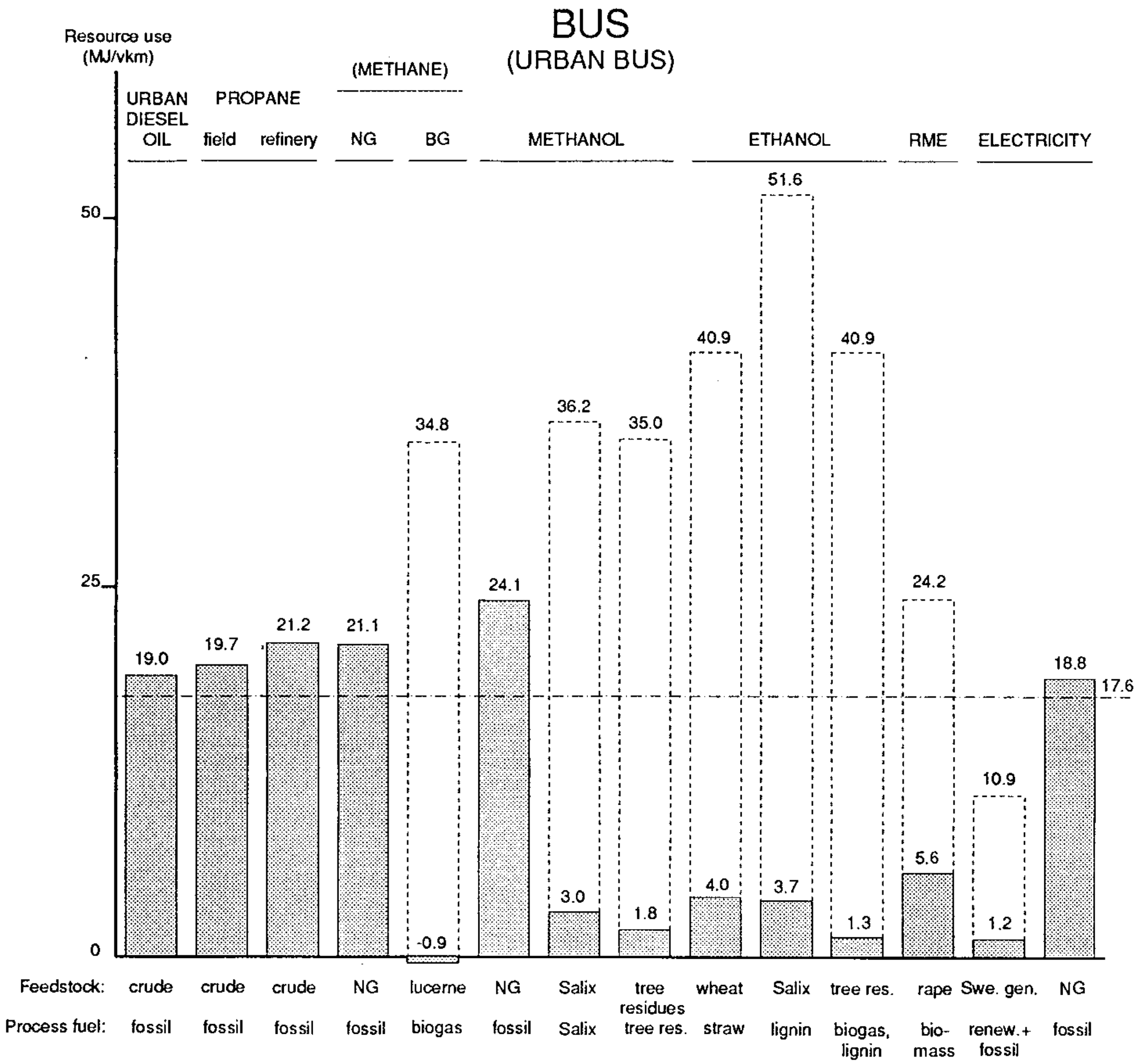

Figure 5.1c Energy resource consumption in BUS model vehicle for fuel chains.

▨	net fossil energy resource consumption	NG=Natural Gas
☐	renewable energy resource consumption	BG=Biogas
—·—··	model vehicle/reference fuel resource consumption (standard diesel oil)	RME=Rapeseed Oil Methyl Ester

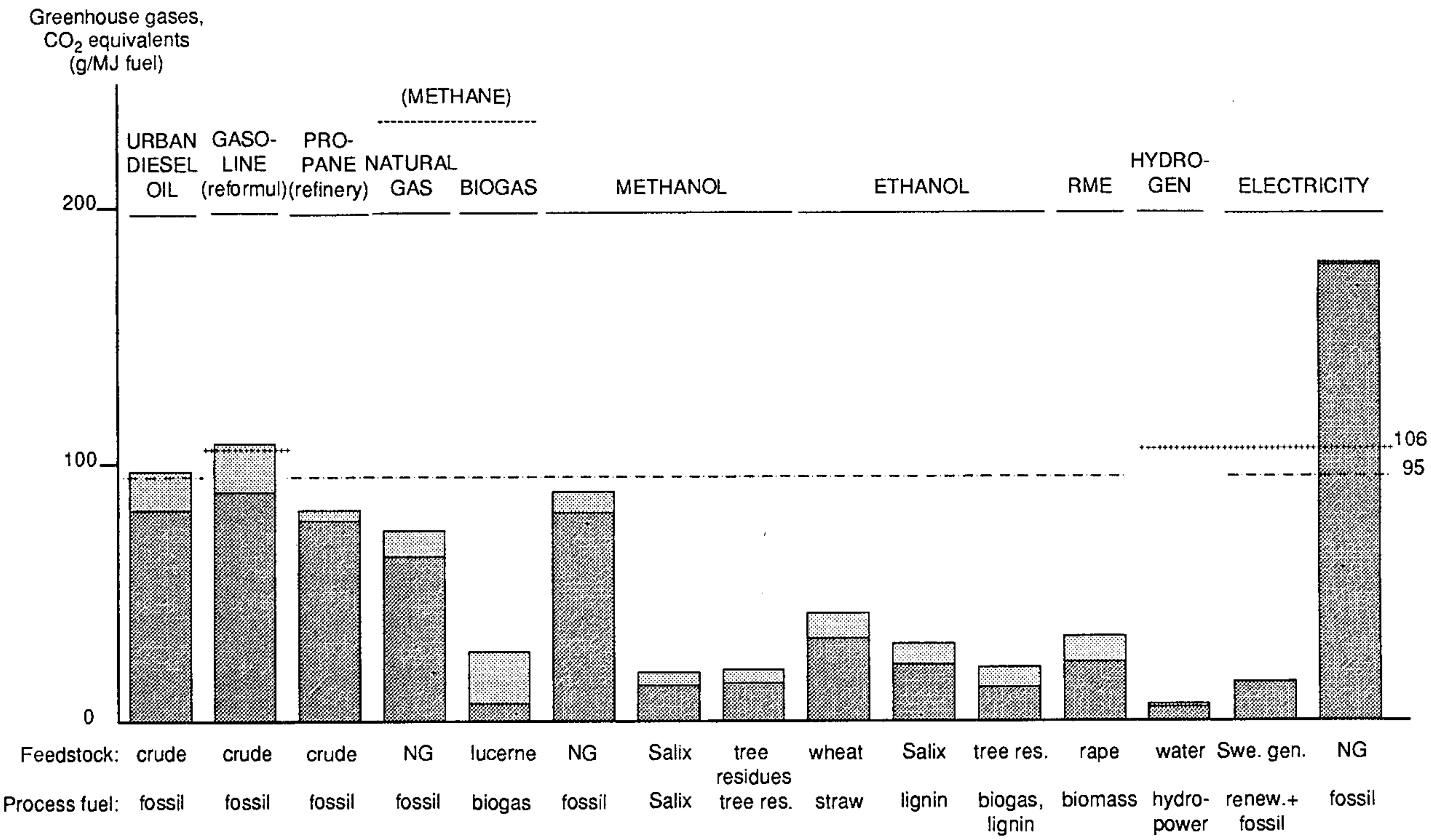

Figure 5.2 Release of greenhouse gases in the fuel chains (biomass based CO_2 omitted; heavy duty bus engines except for gasoline, hydrogen and electricity).

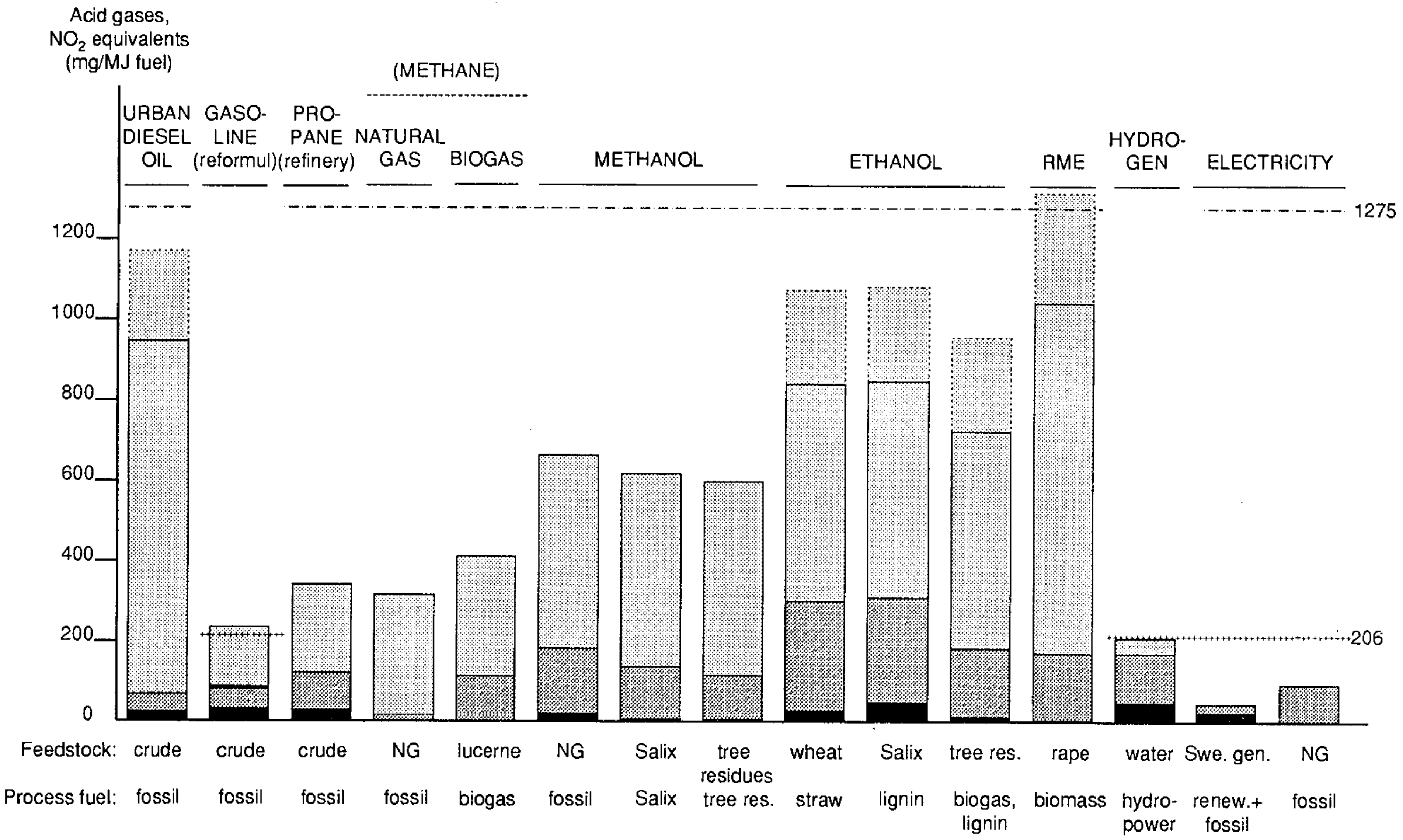

Figure 5.3 Release of acid gases in the fuel chains (heavy duty bus engines except for gasoline, hydrogen and electricity).

6. RESOURCES AND COSTS

In this chapter we try to relate the motor fuels studied to natural resources and costs. We discuss primary energy resources and to what degree those are and could be utilized for the road transport sector of human activities. In this context also world market prices are dealt with. Furthermore, we argue somewhat about costs of diverse character, e g resource costs and commercial costs.

6.1 Primary energy resources

By primary energy we mean the energy in the raw materials for diverse motor fuels. There are, of course, many possible primary energies for a specific motor fuel, as indicated in the study. There is an obvious interest in distinguishing between primary energies of fossil character and those which are renewable. Among the fossil primary energies we place crude oil, natural gas and also peat. Among the renewable ones we place biomass (agro- and forest based), hydro-, wind-, and solar energy.

The resources of the fossil energies are considered to be limited in size, but the size is difficult to measure, since new exploration data and new economies steadily increase the known reserves. However, there is a general consensus that the fossil energy sources are not replenished on a regular basis. Peat may be an exception, but the time scale for reasonable replenishment is some millennia.

The road transport energy end use in OECD countries was about 30 000 PJ in the late 1980s. This constitutes 19 % of the total energy end use and 49 % of the total oil consumption there. In many of these countries the major part of the energy utilized originates from fossil primary energy. For transport, fossil primary energy is totally dominating. In a future with an increasing energy utilization in general, even in the countries which today are not particularly technically developed, and especially with an increased transport energy utilization there, the supply of conventional motor fuels may become critical in many aspects. An increase of fossil base supply could be accomplished by utilizing natural gas and natural gas based fuels (possible for large scale use) and propane or LPG (niche fuel).

Two thirds (2/3) of proven, economically recoverable crude oil reserves are located in The Middle East and three forths (3/4) within OPEC-countries. OECD-countries hold only 6 % of the reserves. Oil recovery within Western Europe is dominated by the North Sea but it covers only about 30 % of the oil consumption in the region. Western Europe, like most industrialized regions, is thus largely and increasingly dependant on imported oil from the Middle East, where costs for the oil extraction are lowest. The interregional trade in crude oil covers about 50 % of the total consumption in the world. The tendency is that crudes are becoming heavier and richer in sulfur.

Reserves of unconventional oils (extra heavy, tar sand, oil shale) are concentrated in the western hemisphere. They are, however, considerably more expensive to recover and refine.

The reserves of natural gas are in energy terms about equal to those of crude oil but utilized only half as much. The potential for increased use of gas is therefore good. The reserves are less concentrated in the Middle East compared to oil but are found mainly in Russia (37 %) and the OECD countries have a larger share, 11 %, than for crude oil. The gas fields in the North Sea, Norwegian Sea and Barents Sea are of particular interest to Western Europe. The West European reserves are about twice as large as those of crude oil.

Transport of gas is both less flexible and more expensive than transport of energy as crude oil and requires very big volumes to justify the cost of pipelines or LNG-plants and ships. The trade in gas is therefore low (14 % of the consumption) and interregionally only 6-7 %, about equally split between pipeline and LNG-shipping.

Propane is recovered from wet gas at natural gas and crude oil extraction and is created at refining of oil, which is the major source in Western Europe. The yield of propane is only a few percent of the energy in crude oil or natural gas. Propane can only be a supplement fuel. Higher use can only be satisfied by imports from regions with surpluses such as the Middle East.

The resources of renewable energies are also limited in a special sense. For instance the hydropower potential of an area could be very limited, but it could generally be relied upon that it will be replenished. In the same way, the wind energy extractable from a specific wind power plant is limited to a certain amount according to wind conditions, but it is fairly certain that this wind energy will be replenished from time to time, although with some variation. For biomass as primary energy the time scale of replenishment varies between types. The agrobased biomass is renewed on a yearly timescale, while the energy forest based has a time scale of some years depending upon climate zone and forestry biomass of one or several decades. The yearly growth of biomass is, however, large and amounts to more than 10 times the total energy usage of the world. The availability of land per capita within a region and suitable growth conditions are decisive for the possibilities for biomass utilization. Brazil, North America, particularly Canada, Sweden and Finland are examples of countries with high biomass potential for local use.

Sweden, having a large land area per capita, has a potential from forestry and agriculture of about 350 PJ of primary biobased energy, which can be transformed to about 175 PJ of motor fuel energy. The Swedish total energy end use was 1300 PJ in 1990, of which about 250 PJ were used for fossil based road transport. A decrease of petroleum dependence could be accomplished by utilizing compressed natural gas or natural gas based fuels as motor fuels. A decrease of fossil energy dependence would demand the utilization of fuels based on renewable sources.

The global biomass energy potential is claimed to be large. Although rain forest areas are rapidly decreasing, desert areas are increasing and food is scarce for many groups of the world's population, the energy content of the global biomass growth is claimed to be about 10 times larger than total global energy usage. It is obviously difficult to administer biomass utilization globally, and as noted in this study the total energy turnover in the biomass system is considerably larger than in the fossil system for the same quantity of motor fuel energy.

In order to, in a way, compensate for this larger total energy requirement of biobased motor fuels, the huge potential of unconventional and thus more 'difficult' energy like solar, wind, and wave including tidal energy could be involved.

To carry the processing of the biomass energy to a motor fuel demands more energy than to bring the biomass into a state which is useful as a combustion fuel in stationary applications. The energy demand difference for fossil based motor fuels and general fuels is smaller. Thus, from a strict energy point of view, it could be argued that fossil energy based fuels preferably should be used in the transport sector. This leaves, however, the growing transport sector almost completely dependent on oil and postpones the build-up of a preparedness to switch over to renewable feedstock base and a sustainable system acceptable also from a climatic point of view.

6.2 World market prices

For conventional primary energies extensive trade activities with well defined world market prices are established. Renewable primary energies are not established in the same manner and also the locality of them and their transportability makes it unreasonable to expect world market prices for them. However, the trade products from them, e g alternative motor fuels, could very well have world market prices, when they are established.

For crude oil and also for the refined products thereof, gasoline and diesel oil, there are world market prices established. The foundations for these prices are not very obvious from a scientific energy point of view. Also some alternative fuel prices are registered and commented upon. In, for instance, the weekly periodical New Fuels Report (Wash D C, USA) there is a new fuels report price watch presenting a compilation of fuel ethanol, methanol, MTBE and gasoline prices in key markets throughout the world. The price per unit volume of fuel ethanol is at present about double the gasoline price.

The electricity grids are getting increasingly interconnected between nations, giving a possible basis for a future world market for electricity.

The fossil primary energy resources are, as so far known, localized to a few regions of the world. For instance, the crude oil deposits that we know of today are largely concentrated in the Arab world. This has obviously affected world politics ever since the second world war, when crude oil business started to boom. The pricing of crude oil in the 1970s demonstrated in practice the problems of the world economy depending too much on a single primary energy source. Actually, much of the effort put into civil atomic energy utilization during the latter half of this century was probably meant to balance the uneven distribution of crude oil deposits.

Today, energy security and environmental aspects are recognized in most countries and also the fact that these matters could be affected by pricing (and taxing). At the meeting in July 1991 between the leaders of the seven leading industrial nations of the world, it was specifically noted in their joint communique that environmental and energy security benefits could be realized from the use of renewable energy. They also pledged that they would seek "to price energy from all sources so as to reflect costs fully, including environmental costs."

One way of including environmental and other resources in the pricing of energy products, is suggested by Howard T Odum of the Environmental Engineering Sciences Department at the University of Florida, Gainesville, FL (USA). His scheme is named EMERGY analysis. The principles of it and several applications of it have been published, e g /57/. We have not found it possible to study and consider to apply this type of analysis within the frames of this study.

6.3 Costs of vehicle operation

The costs of vehicle fuels depend of the prices of primary energies and other commodities and services used in the production process. In comparing the costs of conventional and alternative motor fuels, it is essential to distinguish between the commercial costs - what the purchasers or users pay - and the resource costs. The resource costs are the costs of the natural resources, i e land, materials, labour and capital (including risk capital), consumed, used or imposed in making and distributing the fuels. The difference between the two costs is the result of government taxes on and subsidies to the producers and users of the vehicles /fuels and of allowing the users to consume some resources and impose some costs without payment.

In this study, we try to stick to the resource costs. For conventional fuels this means the commercial cost minus taxes. For alternative fuels with an emerging market it may be the commercial cost plus subsidy, or preferably the cost of resources estimated to be engaged in the production and distribution of the fuel.

Since this is an energy and emissions systems study, it is natural to compare energy-wise the costs per MJ of fuel energy and also per unit of transport work. Emission-wise we will try to present the cost per unit of the main types of emissions considered.

For this we have to deal with the following:

* production costs estimates including by-products and waste at processing primary energies

- infrastructural costs/replacement value

- costs of vehicles for the alternatives.

All three of the above cost items have to be considered in broad features only in a study of this character. Below we present the basic thinking in the cost analyses and exemplify with some figures for the fuels studied.

The renewable alternatives may be of interest to increase the total supply of motor fuels and of special interest in some areas for local economic reasons. However, even for the alternatives the supply possibilities have to be seriously considered when major usage is thought of. For a particular country and for biomass based energy, the land area available and the yields to be expected locally should be intensely studied before larger demonstrations are undertaken. The economics of specific motor fuel plants of commercial size should also be studied as complementary information to possible calculations on combined plants of smaller size in special projects.

6.3.1 Fuel production and infrastructure costs

In a fair comparison, production costs at newly built plants of the same size should be considered for all the alternatives. This is difficult to manage, since e g investment costs for complete plants are not easily available. For the conventional, crude oil based fuels we thus utilize present costs of established qualities and adjust them with estimates of extra costs for the specific qualities required. For the alternative non-conventional fuels in general, we have to rely on estimates presented, and if there are several of them which may disagree, we try to use our own best judgement.

Tentative fuel costs are shown in Table 6.1. Conversions are based on energy contents and densities of the fuels, shown in Table 6.2, when needed. Oil and natural gas based fuels are based on a crude oil price of USD 21 per barrel. To indicate typical average bulk costs at refinery gate, import harbor or landing point/border the following relations are used: For gasoline 1.40, diesel oil 1.10 and propane 0.85 times the crude oil cost on a weight basis. For natural gas the relation is 0.90 on an energy basis. Reformulation of gasoline is assumed to increase the cost by 15-25 % of the refinery gate price and urban diesel oil by nearly 50 %.

Distribution costs, including retailing station mark-up, are taken at SEK 0.75 per liter for gasoline (SEK 23/GJ) and diesel oil (SEK 21/GJ).

Imported methanol from natural gas is assumed to cost 25 % more per energy unit than gasoline. Domestically produced ethanol from lignocellulosic feedstock is projected /85/ to cost SEK 3.25 per liter (E95) ≈ SEK 160/GJ (LHV) in a stand alone plant with favorable feedstock/fuel co-product relation. In an integrated plant (with sulfate pulp mill) a cost of SEK 2.75 per liter ≈ SEK 135/GJ is projected. Methanol produced from biomass would probably cost nearly as much. Biogas production cost with lucerne as feedstock is taken as SEK 100/GJ. Rapeseed oil methyl ester (RME) is illustrated with a production cost of SEK 5/liter ≈ SEK 150/GJ. The production cost of electricity varies between power plants depending on feedstock and age of plant, of course. Hydrogen is considered such an immature alternative that no serious cost estimate can be made. Electricity may in most countries be introduced as a major motor fuel (10% of transport work) on existing power production capacity. In Sweden at present (1991), a small to medium-large electricity consumer (up to 25 MWh per year) has to pay (average for the country) about SEK 0.60/kWh_{el} at the grid outlet. Reducing for VAT (20% of selling price) and special electricity tax (SEK 0.072/kWh), implies a resource cost of about SEK 112/GJ from the grid. The cost of the extractable electric energy from the battery, charger and battery losses included, is then about SEK 165/GJ.

Distribution of methanol and ethanol costs 30 and 25 % more per energy unit than for gasoline because of the bigger volumes to transport and store. Investment costs for new refueling equipment for alcohols are per unit volume the same as gasoline. Adaption of the existing gasoline distribution net to handle alcohols is, at a cost, possible and such costs can be largely reduced if they are made as part of regular maintenance and renewals.

Propane distribution is estimated to be about 50 % more costly than for gasoline because of larger volumes and somewhat more expensive distribution equipment. Natural gas distribution adds about SEK 40/GJ to border import price (SEK 20/GJ) and SEK 5/GJ more for refueling compression. Refueling stations with fast refill possibilities are about four times more costly to build than for liquid fuels.

The production cost at the user's tank as presented above include also most of the infrastructural costs. For example, some extra costs for the surface modification of tanks, pipelines and auxiliary equipment like valves etc to withstand the ethanol are there. Also some costs of preventing excess water inflow to the ethanol volumes, which absorb water in minor quantities with no problems, are included in the 25%.

In general when introducing a new alternative, the costs for the new alternative could be lowered if a reasonable time schedule is kept and good planning is applied. For instance, regulations could be introduced well in advance so that tanks and pipelines can hold several motor fuels, when the times for introduction of the alternatives come. This approach is apparently used in California in preparation for the introduction of methanol.

In Table 6.1 below we present the costs (taxes excluded) at the refueling point for energy from diverse motor fuels per energy unit and per vehicle kilometer for the suitable model vehicles. In addition the specific energy cost is presented in Figure 6.1, where the total cost is presented as composed of the cost at the fuel plant and the costs of distribution and refueling. For electricity the cost in Table 6.1, and thus the total cost in Figure 6.1, is the consumer cost from the distribution grid. The distribution and refueling cost component for electricity in Figure 6.1

is the difference between the consumer cost and the estimated cost for the distributor from the 130 kV power grid (being about SEK 78/GJ).

Table 6.1 **Costs for energy from diverse fuels per MJ (LHV) at refueling and per vehicle kilometer**

Fuel	Energy costs (SEK/GJ)	(SEK/vkm) PC[1/]	MDT[1/]	Bus
standard diesel oil	46	NA	0.46	0.74
urban diesel oil	58	NA	0.60	0.96
standard gasoline	53	0.18	NA	NA
gasoline, reformul.	58-61	0.20	NA	NA
propane	52	0.16	0.57	0.92
natural gas	65[2/]	0.19	0.72	1.17
biogas	105	NA	1.20	1.95
methanol (NG)	68	0.23	0.77	1.25
- " - (tree res.)	110-155	0.34-48	1.13-59	1.83-2.58
ethanol (tree res.)	163-188	NA	1.65-90	2.67-3.07
vegetable oil (RME)	170	NA	1.75	2.80
hydrogen	?	?	NA	NA
electricity	112	0.11	0.79	1.00

[1/] passenger car and medium heavy duty truck resp.
[2/] including 5 SEK for refueling
NA = not applied

Conversions are based on energy contents and densities of the fuels, shown in Table 6.2 below, when needed.

Table 6.2 **Energy content (lower heating value) and density for various motor fuels**

Fuel	Energy content MJ/l	Density kg/l at 15°C
Gasoline	32.5	0.75
-"- , reform.	31.5	0.74
Standard diesel oil	35.5	0.84
Urban diesel oil	35.2	0.83
Propane	23.5	0.51
CNG (per Nm^3)	39*	0.72*
Biogas (per Nm^3)	36*	0.72*
Methanol (M100)	15.8	0.795
Ethanol (E100)	21.1	0.79
-"- (E95)	20	0.80
RME (rapeseed oil)	32.7	0.88
Hydrogen (gas)	10.8*	0.090*

* per Nm^3

6.3.2 Costs of the vehicles

For the vehicles, as well as for the infrastructure tanks, pumps and pipelines, adequate requirements of chemical (and physical) resistance of all components to the new motor fuel have to be considered. For some alternatives, in addition to the development costs of components, the weight and performance of the total vehicle may differ considerably from the conventional vehicle.

Gasoline fueled cars which can meet the future much more stringent emissions regulations will be somewhat more expensive than today's cars due to more sophisticated operation control devices, fuel injection and catalytic clean-up equipment. The additional cost is not yet known with any certainty. In US studies /59, 107/ low-emission car costs are estimated to increase by only 1-2 % in mass production. Alcohol-fueled vehicles and flexible fuel vehicles (FFV) may add another 1-2 % to the cost but in the market there may be no difference at all as is indicated at the emerging marketing of FFVs in the US.

Propane and methane-fueled light-duty vehicles add at least 5 and 10 % respectively to the gasoline-fueled vehicle cost if they are built by OEMs (original equipment manufacturers) because of more expensive pressure tanks for the fuel and fuel injection equipment. Retrofitting outside OEMs is more expensive and may more than double the added costs.

Electrically powered vehicles, when mass produced, will (battery cost excluded) have about the same cost as conventional ones. The cost for one battery, also at mass production level, is expected to add about 20 % to the basic vehicle cost. The technical lifetime of the battery will probably be lower than the basic vehicle life. For a ten year vehicle lifetime, two or three batteries are probably required.

Heavy duty diesel engine vehicles, which can meet much more stringent emission regulations than determined for the near future, will require additional development work. Near term urban vehicles will require improved fuel injection and management and catalytic clean-up systems, which will increase their cost somewhat. We estimate about 5 %. Alcohol-fueled vehicles would probably have to carry some additional costs because of their higher compression ratio, enlarged capacity fuel injection system, bigger fuel tanks and possibly safety devices, as alcohols are inflammable and pose a higher risk than diesel oil. These measures are estimated, supported by projections in US studies, to increase heavy duty vehicle costs 1-2 % at series production. A crucial factor for the additional costs is, of course, the size of the demand so that development and production costs can be spread over a sufficient number of units.

Propane and CNG-fueled heavy duty vehicles will have converted diesel engines to otto cycle operation and complete new fuel system, which is considerably more expensive than for liquid fuels, particularly for CNG because of the many tanks for compressed gas. The weight of these will also reduce the payload and increase transport costs. Retrofitting is today the most common method for the conversion to operation with gas but for the future, OEM production of dedicated vehicles is assumed. The additional costs should be not more than about 5 % higher compared to diesel oil fueled vehicles when produced in sufficient numbers.

6.3.3 Environmental costs

It is a huge task to calculate the environmental costs from a specific type of emission, including in general health costs as well as those related to possible climate changes. It cannot be done within the framework of a study like this. However, we can consider the environmental penalties suggested for some emissions in Sweden and calculate the cost effects of these on the different fuels studied.

The suggested penalties are 40 SEK/kg NO_2, 15 SEK/kg SO_2 and 0.25 SEK/kg CO_2 (fossil) and they are decided on for emissions from industrial activities. Those fees would, if applied to vehicles according to the emissions presented in chapter 4, incur costs for the user of motor fuels as presented in Table 6.3 below.

Table 6.3 Costs for some emissions from different fuels

Fuel	**Emissions costs**					
	(SEK/GJ)*				**(SEK/vkm)**	
	NOx	**SOx**	**CO_2**	**Total**	**Pass.car**	**Bus**
urban diesel oil	44	0.0	18	62	NA	1.03
gasoline, reformul.	5	0.1	19	24	0.08	NA
propane	5/9	0.0	16	21/25	0.07	0.46
natural gas	1/12	0	14	15/26	0.05	0.48
biogas	5/12	0	0	5/12	0.02	0.22
methanol	5/19	0	17	22/36	0.07	0.60
ethanol	22-31	0	0	22-31	NA	0.36--0.51
vegetable oil (RME)	46	0	0	46	NA	0.76
hydrogen	1.4	0	0	1.4	0.004	NA
electricity	0	0	0	0	0	0

* Pass.car value/Bus value when differing
NA = not applied

6.4 Other costs

When considering the economics of a major change of motor fuels' systems and techniques, the environmental/ecological aspects have also to be considered together with the more traditional societal aspects like employment, basic infrastructure investments etc. Among areas to focus on are:

- resource costs, including costs of environment and health
- investments in production, infrastructure and end use techniques

- need and macro-economic cost for training and education
- changes in rate of employment, both for business companies and for the nation
- best return from each invested currency unit conditioning lowest societal cost.

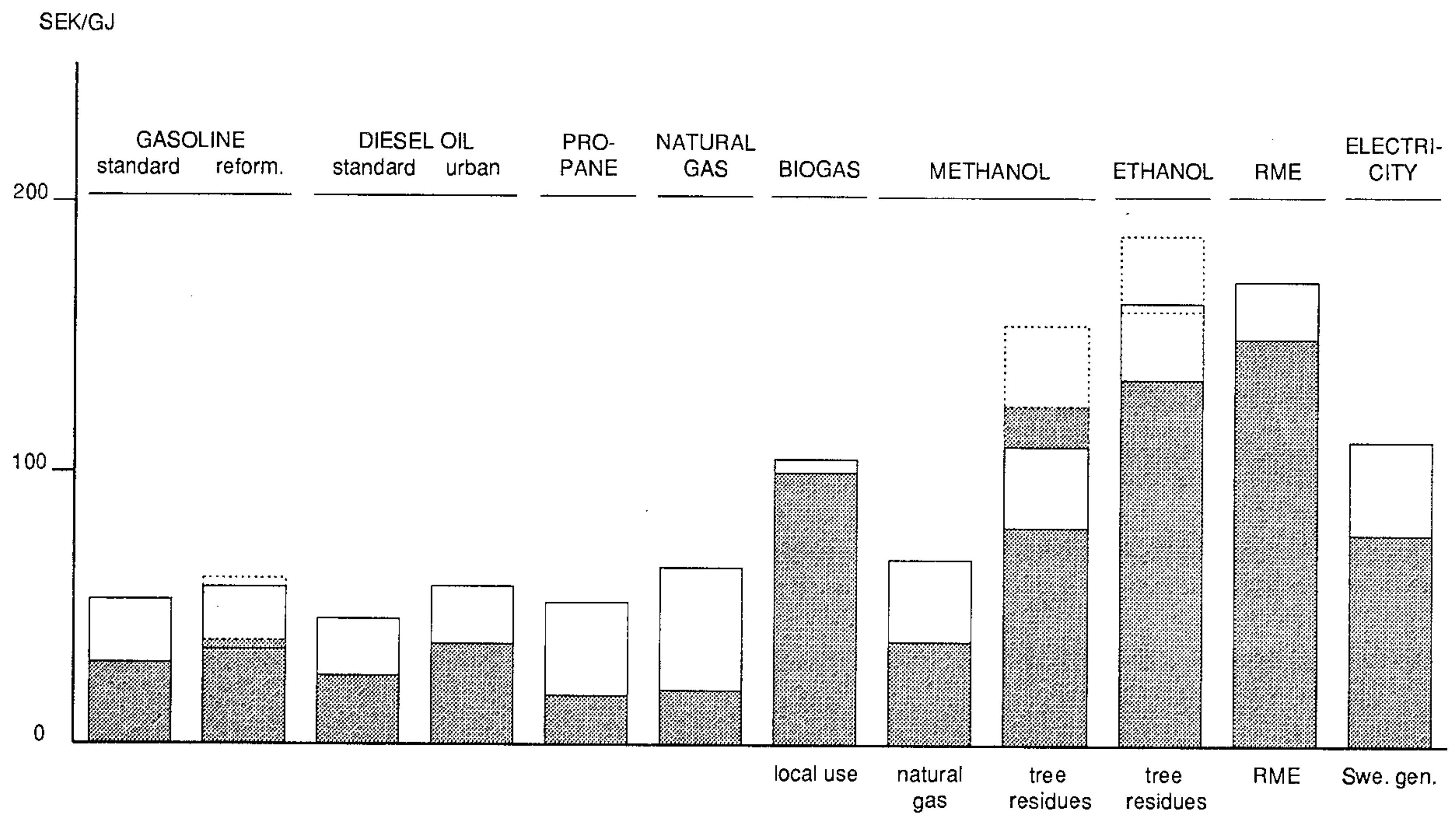

Figure 6.1 Motor fuel cost at refueling station.
(ref. crude at USD 21/bbl = SEK 21x6/159 l = SEK 22/GJ)

▨ Cost at production plant gate /import harbour/border

☐ Distribution + refueling

⬚ range (for any shading)

RME=Rapeseed Oil Methyl Ester

7. CONCLUSIONS

Some conclusions, mainly of general a character, can be drawn from this study. To start with, the method and principles utilized seem to work in practice. We can handle the energies involved in a practical and still fairly stringent way, without having to resort to mere formalism. The energy quality or exergy can, to the best of our judgement, be deatl with in the way used by us.

For the emissions, it seems feasible to get an idea of which are relevant and the quantities of them. When it comes to the effect of the emissions, things are getting a little tougher to handle. It would of course be ideal to get a measure of the total environmental and health loads from the diverse motor fuels. This, however, is obviously not possible at the present stage of knowledge of the contribution to the various types of loads and of the additivity of those loads. Also, on the effect side, there seem to be natural source variations of the same or larger size than the man-made emissions.

For the impact of the various emissions on the greenhouse effect, it seems possible to get a scheme for the addition of contributions from the diverse load components. Of course, there could be debates about the life times of the active compounds as well as about time scales for the release and the binding of CO_2 at various sources. The greenhouse effect is of global dimension only.

Concerning acidifying emissions, mainly sulfur and nitrogen oxides, there is a simple scheme of adding the components, which however does not account for possible synergy effects. The impact of the acidifying emissions find regional and local expressions.

The emissions of oxidant forming precursors are too complex to collect to a single measure of environmental load. Verified air quality models for airborne emissions are available and are used for several purposes with satisfying results. The application of such models requires, however, a lot of computer power and plenty of data. Such model work is outside the scope of this study.

The health hazards from emissions are of two kinds, the acute health damage and the long-term, low level exposure to genotoxic substances of carcinogenic character. For the acute health damaging substances, standards or guidelines for concentrations in air have been listed by WHO or national agencies. These standards or guidelines may be revised now and then, but they are fairly generally accepted, even though often not fulfilled.

There is a large span in the estimated total cancer risk from exposure to the emissions from road traffic in most countries. There are, however, no doubts that the risk is there and of relevant size to be considered. The quantities of carcinogenic emissions can be estimated even though a generally accepted measure of their joint health effect is not yet available. Emerging models have given some results, but the remaining problems with those are outside the scope of this study.

Our study can obviously result in a fairly accurate and complete comparison of the total energy resource requirements, and of most of the environment-affecting emissions released at the application of the motor fuels studied. We have considered the major recognized environmental effects, including some health aspects. Also a rough idea of the major cost items involved in a large-scale application of the respective motor fuels could be anticipated. These results could be used to sort out the alternative fuels which are best suited for possible application in Sweden. When the environmental and health effect data supplied in this study are related to more subtle resource cost calculation and energy supply security aspects are included, the rules for a market competition between the foremost alternative could possibly be set.

Among the specific findings on the fuels studied it is a little surprising that the emissions of acid gases (Figure 5.3 and Table 5.5) are almost the same for urban diesel oil and biomass based ethanol, although the latter could emit only some 80 % at the lower estimate. Even though the end-use emissions clearly dominate, and the emissions considered are definitely larger from urban diesel end use, the higher emissions at the early stages of the biomass based ethanol chain counteract this.

The energy message from the comparison is in a way twofold. Considering fossil energy resources only, it is quite clear that the biomass-based fuels utilizing biomass process fuels are savers. When extended to total energy resource utilization, we find that many of the biomass-based fuels require almost triple the total energy turnover in the full chain as compared to the fossil-based fuels. Biogas and RME, though, require just slightly more total energy than the fossil fuels. (For RME the figures are not quite comparable to the others; see page 40.) An interpretation problem is to find evaluation criteria possibly distinguishing between fossil and renewable (flowing) energy forms. Electricity and to some extent hydrogen are very special in comparison on an energy basis. A unit of electricity does much more transport work on the vehicle than the same unit conventional fuel. (Compare 0.85 to 0.35). Also for hydrogen, the efficiency at the point of use in the vehicle is claimed to be exceptionally high in comparison to conventional fuels, and it also has a potential for electric vehicles via fuel cells.

Based on this study, even if some changes in specific emissions and energy requirements were called for, several specific studies of well defined transport/traffic situations could be performed. A more detailed structure could then be given to the transport work accomplished.

The above and some remarks made in earlier chapters of the study are summarized as follows:

1. Methodology adequate and useful.

2. Emissions sufficiently quantifiable, except for oxidant and health affecting ones, which can only be qualitatively assessed at present because of lack of data.

3. Impacts on health, environment and climate require model calculations, which are beyond the scope of this study; emissions data would serve as input.

4. Energy resource use adequately covered, concluding that
   - energy turnover depends on type of feedstock; 20-300 % higher in renewable systems compared to fossil ones,
   - fuels for end use 17-70 % of resource input in renewable systems compared to 85-90 % for fossil only ones,
   - fossil energy inputs in renewable systems can be only a fraction of that in fossil only ones and may be negative, i.e. the system saves fossil energy elsewhere.

5. Greenhouse-enhancing emissions in the whole fuel chain are somewhat lower for alternative fossil motor fuels (propane, natural gas, methanol) and considerably lower (60-95 %) for renewable systems (hydropower particularly and photosynthesized biomass); emissions expressed as CO_2-equivalents converted by use of IPCC factors, which are not yet finally established.

6. Acid gas emissions combined to common number based on acidifying power but synergistic effects not included; emissions dominated by nitrogen oxides at end use; renewable systems have greater share of acid gas emissions during production; fuel/engine combinations, which allow use of three-way catalytic reduction of nitrogen oxides, show lowest NOx-emission level; alcohols give lower NOx-emissions than diesel oil in diesel engines.

7. Oxidant-forming organic emissions for local conditions (considerably) lower for most alternative fuels due to less reactive fuel components and lower emissions of reactive organic compounds; ranking methane, methanol, propane/ethanol.

8. Genotoxic, cancer initiating/promoting emittants (gaseous alkenes, benzene, aldehydes, NOx (?), particle-bound and semivolatile PACs) lowest for electricity, methane and methanol fuel/engine systems and highest for diesel oil and gasoline.

9. Results of study could be utilized to compare energy resource demand and airborne emissions at various transport scenarios for possible near-future vehicles.

Discussion

In this study many figures of various accuracy have been added and subtracted, which of course has a bearing on the validity of very detailed comparisons between the fuels studied. However, it is obvious that for the impact in any transport scenario the engine efficiencies and the driving patterns of the vehicles are most important. A sensitivity analysis including an extended information collection regarding the end use phase (engine/motor, transmission and driving pattern) could be of interest in order to get a valid way of integrating the pretreatment of motor fuels, being in the focus of this report, with the potentials of various fuels at end use.

Various attitudes could be taken regarding the accuracy of the data for conventional fuels versus those for new fuel alternatives. We feel that the emission levels achievable are more a matter of maturity of concepts, which are perpetually evolving. Detailed information on the composition of emissions is not necessarily better for conventional fuels since detailed analysis is of recent date. Many new techniques have had to be developed and used to give the information needed.

In addition to the above, the following remarks seem proper in this context and in the spirit of the study.

1. Choice of motor fuels in an energy supply view

The renewable alternatives may be of interest to increase the total supply of motor fuels and of special interest in some areas for local economic reasons. However, even for the alternatives the supply possibilities have to be seriously considered when major usage is thought of. For a particular country and for biomass based energy, the land area available and the yields to be expected locally should be intensely studied even before larger demonstrations are undertaken. The economics of specific motor fuel plants of commercial size, matching the size of the motor fuels market, should also be studied as complementary information to possible calculations on combined plants of smaller size in special projects.

As mentioned previously (section 6.1), the conversion of biomass energy to a motor fuel demands more energy than bringing it into a state which is useful as a combustion fuel in stationary applications. The energy demand difference for fossil-based motor fuels and general fuels is smaller. Thus, from a strict energy point of view, it could be argued that fossil-energy based fuels should preferably be used in the transport sector. This, however, would leave the growing transport sector almost completely dependent on oil. Furthermore, it would postpone the build-up of a preparedness to change to renewable feedstock base and a sustainable system acceptable also from a climatic point of view.

2. Needs other than energy supply

Energy supply or conservation is not always the primary criterion. More pressing issues may lead to other choices. Examples of higher value/priority can be:

- when fossil fuels cannot meet stringent emission requirements including new compounds (air toxics such as benzene, aldehydes, PAC)
- when local sources of energy are taken into consideration for land use reasons, for employment reasons or for (national) energy security reasons to name a few.

3. Environmental choice among rated fuels

Other concerns, e g for the environment, could take precedence over energy efficiency. If the need is to:

- reduce greenhouse gases and oxidants, renewable energy in the form of electricity or motor alcohols is preferable
- reduce acid gases, electricity (with due consideration of the generation process) and fossil energy (with the exception of diesel oil) are preferable
- reduce genotoxic emissions, electricity and chemically simple fuels, such as methane and methanol, are preferable.

Nitrogen oxides dominate the acid gas emissions. Since nitrogen oxide emissions originate predominantly from the end use, engine and exhaust gas treatment technologies are important. This importance applies also to genotoxic emissions.

4. Economics for a change of systems and techniques

A major change of systems would need to be analysed from an ecological as well as an economic point of view. Among areas to focus on are:

- resource costs, including costs of environment and health
- investments in production, infrastructure and end use techniques
- need for and cost of training and education
- changes in rate of employment, both for business companies and for the nation
- best return from each invested currency unit to minimize the societal cost.

5. Possible short term actions

Any measures taken today must fulfil the demand of lowest societal cost with respect to benefits and must fit into a long term development of the intended fuels, drive systems, and clean-up systems. Conventional or synthetic hydrocarbon fuels can, at a cost, be considerably improved, which applies also to conventional engine/catalyst techniques. In several respects, the alternative fuels will, however, have an edge over the conventional ones. Still, the latter will dominate for a long time for cost reasons, including the infrastructure costs.

The present state of knowledge concerning the possible introduction of measures to combat air pollution, oil dependence, etc seems to justify the following short term actions:

- The most desirable fuel, electricity (provided it is not produced from oil or coal), suffers from the fact that the electric road vehicle propulsion technique is not sufficiently developed for large market penetration. However, it may constitute a niche fuel if the costs can be accepted. Combustion-engine/battery hybrid drive systems may overcome the present obstacles, but become more of fuel savers than electricity consumers. More R&D efforts are needed and costs have to be accepted. Start demonstration projects which include the infrastructure.

* Gaseous fuels (methane, propane) are also niche fuels, although important, since general availability cannot be made possible and infrastructure and vehicle costs are high. They may be competitive for high mileage vehicles. Present hydrogen production and utilization technology is not acceptable and too costly, which also applies to the infrastructure. There seems to be no reason to produce hydrogen via electricity. Stimulate more demonstration projects. Evaluate ongoing ones and infrastructure.

* Motor alcohols, being liquid fuels, have potential for general availability and large market penetration and have the lowest infrastructure and vehicle costs. The feedstock base is very broad and includes biomass, if costs can be accepted. Motor alcohols can be applied before long and may be competitive (methanol form natural gas) with conventional fuels from new plants. Alcohols can be suitable fuels also in future drive concepts (turbines, fuel cells). Methanol can be seen as a liquid hydrogen carrier. Stimulate more demonstration projects. Evaluate ongoing ones including infrastructure and production alternatives.

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ENERGY FLOWS AND CONCEPTS

For each subprocess (chain link) the energy flow could be presented as in figure 2.1 below.

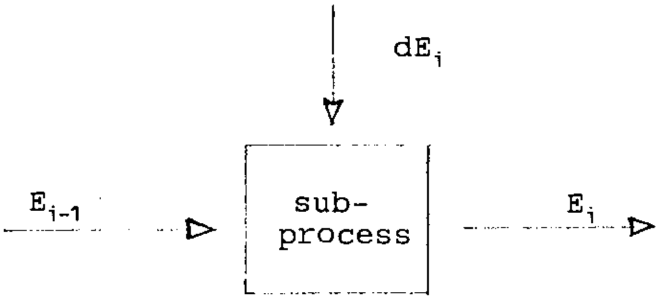

Figure 2.1 Energy flow in subprocess "i" of fuel energy chain

Here E_{i-1} is the energy needed from the fuel main flow of primary energy into the subprocess to supply the energy E_i out of the subprocess. dE_i is the external energy possibly required for the subprocess.

In order to prepare for the formal analyses of the subprocesses and the full fuel chain we define some concepts which we anticipate will be useful.

The energy balance of a process is the total input of energy minus the useful energy coming out of the process. For subprocess "i" the energy balance, ΔE_i, is defined by

$$\Delta E_i = E_{i-1} + dE_i - E_i \qquad ...(1)$$

The specific energy balance of the subprocess, $e_{bal,i}$, is defined by

$$e_{bal,i} = \frac{\Delta E_i}{E_i} = \frac{E_{i-1} + dE_i - E_i}{E_i} \qquad ...(2)$$

In many contexts the energy efficiency of a process is a useful quantity. The energy efficiency of subprocess "i" above is preferably defined by

$$\eta_i = \frac{E_i}{E_{i-1} + dE_i} \qquad ...(3)$$

The formal concepts above are defined for a general subprocess but of course we are interested in entities covering a number of subprocesses and also the total chain. The energy balances of the subprocesses are additive in a simple manner. For example, the energy balance from primary energy source to the end of step 4, that is the fuel in the vehicle tank, is denoted and expressed as follows:

$$\Delta E_{1-4} = E_0 + dE_1 + dE_2 + dE_3 + dE_4 - E_4 \qquad ...(4)$$

It is important to notice that the specific energy balance, $e_{bal,i}$, is not additive. Still it can be a useful concept even for a number of subprocesses or the whole chain. In order to add a number of processes we have to operate via the additive energy balance, $\Delta E_i = e_{bal,i} x E_i$. Thus the specific energy balance up to and including step 4 for instance is preferably denoted by $e_{bal,1-4}$ and defined by

$$e_{bal,1-4} = \frac{\sum_{1}^{4} \Delta E_i}{E_4} \qquad ...(5)$$

The specific energy balance seems from the analytical point of view a bit clumsy to use. However, it has some practical merits in real processes, e g in a petroleum refinery process, where the energy inputs for a specified output of gasoline or diesel fuel are well recorded. For our analysis, where we primarily focus on the energy input to get the fuel energy in the vehicle tank and secondly on what transport work we could get from the fuel in the vehicle tank, $e_{bal,1-4}$ is of special interest. It is the extra energy required to get one fuel energy unit into the vehicle tank all the way from the primary energy source. Note that the fuel energy unit itself is not included.

The quantity $(1 + e_{bal,1-i})$, which we so far have attributed no name, is preferably interpreted to be the quantity of (primary) energy required to get one energy unit at the end of step "i" of the chain. For example, $1 + e_{bal,1-4}$, is the energy required to get one fuel energy unit in the vehicle tank, the fuel energy itself included.

For analytical purposes it is often more convenient to make use of the energy efficiency concept, when dealing with a multistep process. The efficiencies of the subprocesses are multiplied together. For example the energy efficiency of the four first subprocesses together is preferably denoted by η_{1-4} and defined by:

$$\eta_{1-4} = \eta_1 \times \eta_2 \times \eta_3 \times \eta_4 \qquad ...(6)$$

The specific energy balance and the energy efficiency for a subprocess "i" are simply related as follows from their definitions (2) and (3), namely through:

$$e_{bal,i} = \frac{1}{\eta_i} - 1 \qquad \ldots(7a)$$

or

$$\eta_i = \frac{1}{1 + e_{bal,i}} \qquad \ldots(7b)$$

Likewise, the total specific energy balance for a number of subprocesses, $e_{bal,1-i}$, and the total energy efficiency for the same subprocesses, η_{1-i}, are related by similar equations as can be understood from the interpretations above.

Another way of examining the net energy is by the NUEP (Net Utilizable Energy Production) concept /104, 105/. It is defined as

$$\frac{\text{externally utilizable energy - secondary energy input}}{\text{primary energy available (raw materials)}} \times 100$$

As applied to this study, the numerator refers to motor fuel energy and the denominator to used primary energy allocated to the motor fuel in proportion to its energy share of all the output products. No consideration is given to different utilization of subprocesses at the allocation.

The NUEP approach offers another way of presenting the energy analysis and gives another set of figures for comparison. The numbers cannot be directly compared. We have chosen not to use the NUEP approach.

APPENDIX 3.1

A. SWEDISH STANDARD FOR DIESEL OILS

SIS-STG 1991-02-18 **Utgåva 1**

ASTM D 3120	Trace quantities of sulfur in light liquid petroleum hydrocarbons by oxidative microcoulometry
ASTM D 4045	Sulfur in petroleum products by hydrogenolysis and rateometric colorimetry
ASTM D 4052	Density and relative density of liquids by digital density meter
ASTM D 4294	Sulfur in petroleum products by non-dispersive X-ray flourescence spectrometry
ASTM D 4737	Calculated cetane index by four variable equation.

3 Krav

Krav rörande egenskaper framgår av tabellen i bilagan.

4 Provtagning

För manuell provtagning gäller SS-ISO 3170 och för automatisk provtagning ur rörledning SS-ISO 3171.

5 Beteckning

En dieselbrännolja enligt denna standard anges med beteckning enligt tabell 1 följd av standardens beteckning.

Tabell 1 - Beteckning för dieselbrännolja för snabbgående dieselmotorer

Dieselkvalitet	Beteckning
Tätortsdiesel enligt miljöklass 1	TD1
Tätortsdiesel enligt miljöklass 2	TD2
Normal sommar-diesel	D10
Vinterdiesel 1	D26
Vinterdiesel 2	D32
Vinterdiesel 3	D38

3 Requirements

Requirements for properties apply as set forth in the the annex.

4 Sampling

For manual sampling SS-ISO 3170 shall apply and for automatic sampling from pipelines SS-ISO 3171.

5 Designation

A diesel fuel oil in accordance with this Swedish standard is stated with designation in accordance with table 1 followed by the designation of the Swedish standard.

Table 1 - Designation for diesel fuel oil for high-speed diesel engines

Quality of diesel	Designation
Urban diesel 1	TD1
Urban diesel 2	TD2
Normal summer diesel	D10
Winter diesel 1	D26
Winter diesel 2	D32
Winter diesel 3	D38

BILAGA
KRAV FÖR DIESELBRÄNNOLJA FÖR SNABBGÅENDE DIESELMOTORER
(Denna bilaga är en integrerad del av standarden.)

ANNEX
REQUIREMENTS ON DIESEL FUEL OIL FOR HIGH-SPEED DIESEL ENGINES
(This annex forms an integral part of the standard.)

Egenskap/Property	Enhet/Unit	Krav/Requirement						Provningsmetod/Test method
		TD1	TD2	D10	D26	D32	D38	
Tändvillighet Ignition quality (cetanindex), min (Cetane index), min		50	47	46	46	46	43	ASTM D 4737 1)
(cetantal), min (Cetane number), min		50	47	49	47	46	45	SS 15 51 64 2) (= ISO 5165)
Viskositet vid 40 °C Viscosity at 40 °C	mm^2/s (cSt)	1,2-4,0 3)	1,2-4,0 3)	2,0-4,5	1,5-4,0	1.5-4,0	1,4-4,0 3)	SS 02 35 10 (= ISO 3104)
Densitet vid 15 °C Density at 15 °C	kg/m^3	800-820	800-820	820-860	800-845	800-840	800-840	ISO 3675 ASTM D 4052
Svavel masshalt, max 4) Sulphur content, max 4)	%	0,001 5)	0.020 5)	0,3 6)	0.3 6)	0,3 6)	0.3 6)	EN 41, ASTM D 2622, ASTM D 3120, ASTM D 4045, ASTM D 4294, ISO 4260 ISO 8754
Filtrerbarhet i kyla (CFPP) Cold Filter Plugging Point Sommarkvalitet Summer quality	°C	-10	-10	-10				SIS 15 51 22, IP 309
Vinterkvalitet Winter quality		-26 7)	-26 7)		-26	-32	-38	
Grumlingstemperatur, max Cloud point, max Sommarkvalitet Summer quality	°C	± 0	± 0	± 0				
Vinterkvalitet Winter quality	°C	- 16 7)	- 16 7)		-16	-22	-28	ASTM D 2500
Destillation Distillation Begynnelsekokpunkt, min Initial boiling point, min	°C	180 5)	180 5)					SS-ISO 3405
Temp vid 10 % destillat, min Temp at 10 % recovery, min	°C				180	180	180	
Temp vid 65 % destillat, min Temp at 65 % recovery, min	°C			250				

Temp vid 85 % destillat, max Temp at 85 % recovery, max	°C			350				
Temp vid 95 % destillat, max Temp at 95 % recovary, max	°C	285 5)8)	285 5)8)	370	340	340	340	
Slutkokpunkt, max Final boiling point, max	°C	300 5)8)	300 5)8)					
Flampunkt 9), min Flash point 9), min	°C	56	56	56	56	56	56	SS-ISO 2719
Vatten (masshalt), max Water content, max	%	0,01 10)	0,01 10)	0,02 10)	0,02 10)	0,02 10)	0,02 10)	ASTM D 1744
Vatten och sediment (volymhalt), max Water and sediment content, max	%	0,05 11)12)	0,05 11)12)	0,05 11)12)	0,05 11)12)	0,05 11)12)	0,05 11)12)	ASTM D 2709
Aska (masshalt), max Ash content, max	%	0,01	0,01	0,01	0,01	0,01	0,01	SS 15 51 06 (= ISO 6245)
Kokstal (Ramsbottom) (masshalt), max Carbon residue, max	%	0,2 13)	0,2 13)	0,2 13)	0,2 13)	0,2 13)	0,2 13)	SS 15 51 66 (= ISO 4262)
Korrosiv inverkan på koppar, 3 h vid 50 °C, max Corrosiveness to copper, 3 h at 50 °C, max	enligt skala according to scale	1	1	1	1	1	1	SS-ISO 2160
Aromathalt (volymhalt), max Aromatic content, max	%	5 5)14)	20 5)	inget krav	inget krav	inget krav	inget krav	ASTM D 1319 IP 391
Oxidationsstabilitet, max Oxidation stability, max	mg/100 ml	2,5	2,5	2,5	2,5	2,5	2,5	ASTM D 2274

B. CLASSIFICATION OF URBAN DIESEL OILS IN SWEDEN

The classification of urban diesel oils was introduced in Sweden Jan.1, 1991, (accompanied by differentiation in taxation). The classification was altered somewhat as of Jan.1, 1992. The table below shows the definition of the classes.

	1991		From 1992	
	Class 1	Class 2	Class 1	Class 2
Sulfur, max.ppmw	10	200	10	50
Aromatics, max.vol%	5	20	5	20
PAH, max. vol% *	-	-	0.02	0.1
Cetane index	-	-	50	47
Density, kg/l	-	-	800-820	800-820
Distillation				
range,°C	180-300	180-300	-	-
IBP, °C	-	-	180	180
T95, °C	-	-	285	295

* Determined by HPLC-method (IP 391 modified)

C. REFORMULATED GASOLINES

Gasoline standards do not normally set any limits for the composition of types of hydrocarbons (exception benzene). In the 1990 revised Clean Air Act (CAA) in the U.S. the EPA has been given the authority to prescribe some such limits and in California a second phase of reformulation has recently been decided. The purpose is to reduce emissions of oxidant forming compounds and of "air toxics" (benzene, 1,3-butadiene, PAC, formaldehyde, acetaldehyde). In the table below a number of data are given as target values, with today's average US and European gasoline for comparison, and one example of ARCO's proposed gasoline. There are also higher maximum values for single shipments and lower values for so called averaging.

	CAA	Calif. phase II	US average	Eur. average	ARCO EC-X
	class B				
RVP, kPa	56	49	60	76	46
Benzene, vol%	1.0	1.0	1.5	2.6	0.8
Aromatics, vol%	-	28	32	40	22
Olefins, vol%	*	7	9.7	7	5.5
Oxygen, wt%	2.0	≈2	0.4	0.0	2.7
T50, °C	-	99	101	-	94
T90, °C	*	154	166	≈160	145
Sulfur, ppmw	*	40	339	≈150	41

* no greater than refiner 1990 average

The gasoline according to the CAA must be certified by EPA by engine testing or calculation model for emissions performance. It shall give (from 1997) at least 16.5 % reduction in VOC emissions and "air toxics" with no increase in NOx emissions.

The RVP requirement is area dependent according to climate both in the U.S. and in W.Europe. The W.European gasoline pool holds somewhat higher clear octane (unleaded) level than in the U.S., RON 95 and 93.5 respectively.

APPENDIX 4.1

CALCULATION OF EMISSIONS - **GASOLINE AND DIESEL OIL**

Base data and transformations in the different steps of the fuel chain crude oil to reformulated gasoline and diesel oil.

Crude recovery. Fuel: Wet natural gas and minor amounts of diesel oil. Use in gas turbines, heaters, flare and diesel engines. Consumption 3 % based on total finished products.
Specific emissions in $mg/MJ_{fuel:}$ NOx-280, NMHC-50, CO-40 á 170, CH_4-110, N_2O-1.5, CO_2-60 g/MJ_{fuel}. Source: Ref. 45 and 62.
Specific emissions based on finished products: Multiply with 0.03
Methane leakage of 0.1 % (energy) added ≈ 23 mg $CH_4/MJ_{finished\ fuel}$.

Sea transport. Fuel: Bunker C-oil, 3-3.5 %w sulfur, LHV-40 MJ/kg, carbon content ≈ 90 g CO_2/MJ. Use in big 2-stroke diesel engines with thermal efficiency of 60 %. Consumption 0.7 % based on energy in finished products.
Specific emissions in g/kWh_{work}: NOx-17, CO-0.3, THC-0.9. Source ref.64. CH_4-20, N_2O-5 mg/MJ_{fuel}. Source ref. 86.
Specific emissions based on finished products:
SOx: 30000·2·0.007:40 ≈ 10 $mg/MJ_{finished\ fuel}$
NOx: (17000:3.6)·0.6·0.007 ≈ 20 $mg/MJ_{finished\ fuel}$
CO: ≈ 0.4 "
THC: ≈ 1 "
CH_4: 0.007·20 ≈ <<1 "
N_2O: ≈ <<1 "

Refining. Fuel: Refinery gases (3/4) and HFO and coke (1/4). Consumption 7.5 % based on crude oil (LHV 42 MJ/kg), 8 % on total finished products.
Specific emissions in mg per kg crude oil refined: SOx-340(-450), NOx-200, HC-350, CH_4 no data. CO_2-250 g. Source: Ref. 62 and Scanraff emission report 1988. N_2O-15 mg/MJ crude oil. Source ref.86.
Energy usage allocation: Reformulated gasoline 15.5 %, urban diesel oil 9 % on basis of finished product.
Specific emissions based on finished fuel:
Gasoline. SOx: (340:42)·(15.5:7.5) ≈ 17 mg/MJ
NOx: ≈ 10 "
HC: ≈ 17 "
N_2O: ≈ 2 "
CO_2: ≈ 12 g/MJ
Urban diesel oil. SOx: (340:42)·(9:7.5) ≈ 10 mg/MJ
NOx: ≈ 6 "
HC: ≈ 10 "
N_2O: ≈ 1.5 "
CO_2: ≈ 7 g/MJ
CO-emission estimated to be very low.

Distribution. Fuel: Urban diesel oil used in road tankers equipped with catalyst. ≈10 ppmw sulfur. 35.5 MJ/liter. ≈72 g CO_2/MJ. Fuel consumption 0.4 lit./vkm. Energy usage for distribution ≤1 % of finished fuel.

Specific emissions in g/vkm: NOx-15, CO-1.0, HC-0.5, CH_4-6 % of HC, N_2O-<3 %of NOx, SOx-<0.01.
Specific emissions based on finished fuel:
NOx: (15000·0.01):(0.4·35.5) ≈ 10 mg/MJ
CO: ≈ <1 "
HC: ≈ <1 "
CH_4: ≈ <<1 "
N_2O: ≈ <<1 "
CO_2: ≈ 0.7 "

At gasoline distribution evaporative losse are estimated to ≤0.15 vol% of light hydrocarbons (density 0.6 kg/l). This translates to $0.0015 \cdot 0.6 \cdot 1000^2 : 32.5 \sim 30$ mg/MJ gasoline.

<u>End use in bus</u> equipped with catalyst, using urban diesel oil. Fuel consumption 0.45 lit./vkm plus 4 % because of the catalytic system (≈16.6 MJ/vkm). 10 ppmw sulfur.
Specific in-use emissions (projected) in g/vkm: NOx-14-18, CO-0.5, HC-0.5, CH_4-0.09, N_2O-0.3-3 % of NOx.
Specific emissions based on MJ finished fuel.
NOx: 14,-18,000:16.6 ≈ 840-1100 mg/MJ
CO: ≈ 30 "
HC: ≈ 30 "
CH_4: ≈ 5 "
N_2O: ≈ 3-35 "
SOx: ≈ 0.5 "
CO_2: ≈ 72 g/MJ

<u>End use in passenger car</u> with catalyst using reformulated gasoline. Fuel consumption 0.105 lit./vkm ≈ 3.4 MJ/vkm. ≤100 ppmw sulfur.
Specific in-use emissions (projected at 80,000 km under real driving conditions) in g/vkm: NOx-0.4, CO-6, HC-0.84, CH_4-0.1, N_2O-0.07, CO_2-256. Source: Ref. 51 and 103.
Specific emissions based on MJ finished fuel:
NOx: 400:3.4 ≈ 120 mg/MJ
CO: ≈ 1760 "
HC: ≈ 250 "
CH_4: ≈ 30 "
N_2O: ≈ 20 "
SOx: ≈ 5 "
CO_2: ≈ 75 g/MJ

CALCULATION OF EMISSIONS - **PROPANE**

Base data and transformations in the different steps of the fuel chain crude oil/natural gas recovery to propane.

Propane feedstock (crude oil, wet natural gas) recovery. Fuel, energy usage and emissions as for crude oil recovery (appendix 4.1). Less flaring could be expected at natural gas recovery as this is the main product. On the other hand more energy would be used for gas compression to prepare and move gas to the wet gas terminal for processing. The net effect is assumed to lead to no change in energy usage compared to crude oil recovery.

Sea transport. Applies to crude oil. See appendix 4.1.

Wet gas terminal. Fuel: (Wet) Natural gas used in turbines and heaters. Consumption 2 % based on total finished products. Specific emissions as at crude oil/natural gas recovery (appendix 4.1) Methane leakage of 0.1 % (energy) added ≈ 22 mg $CH_4/MJ_{propane}$.

Refining. As described for gasoline and diesel oil (appendix 4.1). Propane appears in the gasoline train as co-product from reformer and crackers. A share of the energy usage in these units and distillations is allocated to propane and is estimated to be 10 % of the propane produced in energy terms.
Specific emissions based on MJ propane:
SOx: (340:42)·(10:7.5) ≈ 11 $mg/MJ_{propane}$
NOx: ≈ 6 "
CO: ≈ 11 "
N_2O: ≈ 0.3 "
CO_2: ≈ 8 $g/MJ_{propane}$
CO-emission estimated to be very low.

Sea transport from refineries or wet gas terminals to terminals for further land distribution. Fuel consumption 1.5 % and 1.0 % of propane transported for field and refinery propane respectively. Emissions as at sea transport in appendix 4.1 except for SOx because a heavy fuel oil with 0.5 % sulfur is assumed as ship fuel.

Land distribution. As for gasoline and diesel oil (appendix 4.1) but urban diesel oil consumption is 1.5 % of the propane-energy transported. Fugitive losses from pressure tanks are considered to be negligible.

End use in passenger car equipped with lambda-one control and 3-way catalyst. Fuel consumption 0.132 lit./vkm ≈ 3.1 $MJ_{propane}$/vkm. Few test data for dedicated propane-fueled cars are available. In comparison to gasoline-fueled cars substantially lower CO and somewhat lower HC-emissions are sasumed. Fugitive losses from vehicle pressure tank are considered to be negligible.
Specific in-use emissions (projected) in g/vkm: NOx-0.4, CO-1.5, HC-0.6, CO_2-202. No data for CH_4 and N_2O but are assumed equal as for gasoline-fueled engine.

Specific emissions based on MJ propane:
NOx: 400:3.1 ≈ 130 $mg/MJ_{propane}$
CO: ≈ 480 "
HC: ≈ 195 "
CO_2: ≈ 65 $g/MJ_{propane}$
CH_4: ≈ (30) $mg/MJ_{propane}$
N_2O: ≈ (20) "

End use in <u>urban bus</u> equipped with lambda-one control and 3-way catalyst considered to be needed to meet future NOx-limit goals. Fuel consumption on energy basis as for CNG-fueled engine projected to be 10 % higher than in diesel oil-fueled engine (appendix 4.1): 1.1 · 16.6 = 18.3 MJ/vkm.
There are no test data available for dedicated, heavy-duty propane engines, which use the otto-cycle. Estimated emissions are speculative and may be optimistic but express a potential.
Specific in-use emissions (projected) in g/vkm: NOx-4, CO-2.5, HC-1, CO_2-1190. No data for CH_4 or N_2O.
Specific emissions based on MJ propane:
NOx: 4000:18.3 ≈ 220 $mg/MJ_{propane}$
CO: ≈ 135 "
HC: ≈ 55 "
CO_2: ≈ 65 $g/MJ_{propane}$.

APPENDIX 4.3

CALCULATION OF EMISSIONS - **METHANE**

1. Base data and transformations in the different steps of the fuel chain of **natural gas.**

Extraction/preparation. Fuel: As for gasoline and diesel oil wet natural gas is used as major fuel (appendix 4.1). The difference to the former case is that the gas is also used in compressor stations in order to transport the gas to the processing plant. Less flaring of gas is assumed when gas is the main product and the emissions values and the same fuel consumption figures are used as in the gasoline/diesel oil case. The consumption of 3 % is used based on finished natural gas.

The losses of methane are estimated to be 1 % of final energy output for the whole fuel chain and this loss is equally split between the three first steps in the fuel chain. The losses are calculated to consist of methane even if natural gas also contains small contents of heavier hydrocarbons.

Methane weighs ~720 g/Nm^3. 1 Nm^3 of natural gas has a lower energy value of ~39 MJ. (0.01 x 720) : 39 = 184 mg/MJ$_{\text{natural gas}}$.
184 : 3 ≈ 61 mg/MJ for each step.

The values, columns 1 and 2, are based on sources 45 and 62.

	Specific emission mg/MJ$_{\text{fuel}}$	Spec. emission mg/MJ$_{\text{CNG}}$
NO_x	280	8.4 (280 · 0.03)
NMHC	50	1.5
CO	40-170	3.2 (mean value)
CH_4	110	3.3[1]
N_2O	1.5	0.04
CO_2	60000	1800
SO_x	<< 1	<< 1

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[1] To be added to the 61 mg/MJ methane loss calculated above.

Processing. Fuel: Wet natural gas. The same specific emissions in mg/MJ$_{\text{fuel}}$ as for the extraction/preparation process. An energy need of 2 % of finished fuel will then result in the following figures:

NOx	5.6 (280 · 0.02)	mg/MJ$_{\text{CNG}}$
NMHC	1	"
CO	2.1	"
N_2O	0.03	"
CO_2	1200	"
SO_x	<< 1	"
CH_4	62	" (incl. loss)

Distribution, End compression. Fuel: All energy for these operations is assumed to be covered by electricity supplied by the grid. As mentioned in chapter 2 all electricity used from the grid in these calculations is produced in a natural gas power plant with an efficiency of 47 %, including distribution losses of the electricity. The specific emissions values for a modern gas power plant are given below /76/. N_2O-data /86/.
The distribution and end compression processes together demand 9 % of the energy in the finished fuel.

	mg/MJ_{fuel}	mg/MJ_{CNG}	
CO_2	56000	5040	$(56000 \cdot 0.09)$
NOx	20	1.8	
CH_4 1)	3	0.3	
N_2O	5	0.5	

Total CH_4-emission: 62 mg/MJ_{CNG} including loss.

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1) Emission given as HC but assumed to be almost 100 % CH_4.

End use in bus with a three-way catalyst. Fuel consumption 10 % higher than diesel oil in energy terms (efficiency 32 %). The figures are based on the Co-Nordic Gasbus project which measured the emissions on engine dynamometer according to the heavy duty-FTP-cycle. To obtain the emissions according to the German (Braunschweig) bus-cycle standard a factor of 1.25 is used. Also a time factor of 10 % is added to compensate for ageing. Of the total HC emissions 10 % is assumed to be non-methane emissions. Fugitive losses from vehicle pressure tanks are considered to be negligible.

	FTP, g/kWh			g/MJ_{CNG}	g/vkm (18.5 MJ/vkm)
NO_x	2.46	$(2.46 \cdot 1.25 \cdot 1.1):3.6 \cdot 0.32$	≈	0.30	5.5
NMHC	0.148		≈	0.018	0.33
CH_4	1.33		≈	0.16	2.9
CO	1.36		≈	0.17	3.1
Part	0.02		≈	0.003	0.05
CO_2			≈	56	1035
Formaldehyde 1)	0.0008		=	0.0001	0.002

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1) Source 67

CNG instead of diesel oil leads to a higher weight for the fuel system. A reference diesel oil tank is estimated to contain 300 litres of diesel oil and the total weight of the system is then ≈ 300 kg. The same energy content of CNG fuel has a weight of 240 kg and will need 1200 litres of storage volume (200 bar). High pressure storage cylinders (composite) have a weight of ~0.5 kg/litre, which gives the tank system a weight of 600 kg. As result the extra weight for the CNG system will be 840-300 = 540 kg, which corresponds to 3.4 % of the total vehicle weight or 4.3 % at average payload. 1 % of increased vehicle weight normally leads to an increasing fuel consumption of 0.33 %, which gives an extra consumption of ~1.4 % for a CNG bus.

End use in passenger car with catalyst. Fuel consumption ≈ 3.1 MJ/vkm.
Specific in-use emissions (projected) in g/vkm: NO_x: 0.4, CO: 1.5, NMHC: 0.03, CH_4: 0.6, CO_2: 174.
Specific emissions based on MJ CNG:

NO_x: 400:3.1 ≈ 130 mg/MJ_{CNG}
CO: ≈ 480 "
NMHC: ≈ 10 "
CH_4: ≈ 190 "
CO_2: ≈ 56 g/MJ_{CNG}

2. Base data and transformations in the different steps of the fuel chain **biogas from lucerne.**

Cultivation, harvesting. The same base data are used for biogas as in the ethanol appendix 4.5. Natural gas is used to produce fertilizers and chemicals. Diesel oil (10 ppmw sulphur) is used for tractors. Specific emissions for each category:

Diesel-tractor: NOx: 1170, CO: 240, HC: 150 mg/MJ_{fuel}, CO_2: 72 g/MJ_{fuel}
Fertilizer: NOx:≈80-180, CO:≈25, CH_4≈40 mg/MJ_{fuel}, CO_2: 56 g/MJ_{fuel}

Diesel fuel for tractors requires 88 % of the energy need (4 %) in the cultivation/harvesting process, which corresponds to 0.035 MJ/MJ_{fuel}. The remaining 12 %, 0.005 MJ/MJ_{fuel}, is used for production of fertilizers. Resulting emissions:

NO_x: 1170 · 0.035 + 130 · 0.005 ≈ 42 mg/MJ_{biogas}
CO: ≈ 8 "
NMHC: ≈ 5 "
CH_4: ≈ <<1 "
N_2O: ≈ <1 "
CO_2: ≈ 3 g/MJ_{biogas}

Transport (lucerne, residue). Trucks with emissions as for road tankers (appendix 4.1). Energy usage 4 % of MJ biogas energy. Specific emissions per MJ biogas:

NOx: (15000 · 0.05):(0.4 · 35.5) ≈ 42 mg/MJ_{biogas}
CO: ≈ 3 "
HC: ≈ 1 "
CH_4: ≈ <<1 "
N_2O: ≈ <1 "
CO_2: ≈ 3 g/MJ_{biogas}

Conversion. For the digestor process electricity and heat are generated by burning biogas. The total demand for these processes are 17 % of the produced biogas. The specific emission values for production of electricity and heat in smaller cogeneration plants with catalysts are as follows /68/:

NOx: 50-100 mg/MJ_{fuel} 75 · 0.17 ≈ 13 mg/MJ_{biogas}
CO: 25 " ≈ 4 "
CH_4: 40 " ≈ 7 "
CO_2: 55 g/MJ ≈ 9.4 g/MJ_{biogas}

No data for N_2O.

3 % of finished biogas and its methane is estimated as losses. 1 Nm^3 of methane weighs ~720 g. 0.03 x 720 ≈ 22 g/Nm^3, which gives a methane loss of ~600 mg/MJ_{biogas}. Total emission of methane connected to the conversion process step ≈ 607 mg/MJ_{biogas}.

Purification/compression needs mainly electricity, which is supplied as in the conversion step. 17 % of the biogas will be needed. Most (80 %) of the CO_2 in the biogas (25 vol%) is removed in the purification step and released to the atmosphere:
$0.8 \cdot 0.25 \cdot 1950 : 27 \approx 14$ g CO_2/MJ_{biogas} to be added to the release by the combustion (below).

NOx:	$75 \cdot 0.17 \approx$	13 mg/MJ_{biogas}
CO:	≈	4 "
CH_4:	≈	7 "
CO_2:	≈	9.4 g/MJ_{biogas}

End distribution will demand only a small share, 1 %, of the energy in biogas. Also in this step the compression work is generated by electricity from smaller cogeneration plants.

NO_x:	$75 \cdot 0.01 \approx$	1 mg/MJ_{biogas}
CO:	≈	<1 "
CH_4:	≈	<1 "
CO_2:	≈	0.55 g/MJ_{biogas}

End use emissions will be the same for biogas as for natural gas except that carbon dioxide is of biomass origin. The biogas does not contain higher hydrocarbons but has a residual CO_2-content of about 6 vol% not removed in the purification step. This increases the CO_2-emission to about 58 g/MJ biogas.

CALCULATION OF EMISSIONS - **METHANOL**

Base data and transformations in the different steps of the fuel chains natural gas to methanol and biomass to methanol.

Natural gas recovery. As described for propane (appendix 4.2). Fuel consumption 3 % based on finished methanol energy. The somewhat lower energy usage based on natural gas recovered than in the propane chain is caused by (on average) less flaring. Methane leakage of 0.3 % energy added ≈ 87 mg $CH_4/MJ_{methanol}$.

Wet gas terminal. Wet gas processing is omitted in the methanol chain as the methanol plant operates preferably on wet natural gas.

Conversion. Fuel: Purge gas (hydrogen and methane) and supplementary natural gas. Use in reformer burners and heaters. Methanol yield as good average value in future, self-sustaining plants estimated to be somewhat over 70 % on energy basis (LHV), corresponding to energy usage to run the plant of 0.40 MJ per $MJ_{methanol}$. Carbon conversion to methanol is assumed to be 90 %, corresponding to CO_2 release of 8 $g/MJ_{methanol}$. Other emissions as for natural gas recovery with 0.1 % leak of methane added.

Sea transport. As described for crude oil (appendix 4.1) for imports to coast terminals. Fuel consumption 1.2 % of the methanol load in energy terms.

Land distribution. As for gasoline and diesel oil (appendix 4.1). Energy usage about 1 % of the methanol. In the domestic case, biomass based methanol distribution is assumed to use 2 % in energy terms. Mass evaporative losses are assumed to be one third compared to gasoline and less than half as reactive in the atmosphere. This translates to a HCE loss of about 4 $mg/MJ_{methanol}$.

End use in passenger car. Dedicated M100-otto engine with 3-way catalyst. Projected fuel consumption 0.195 lit./vkm ≈ 3.05 MJ/vkm, i.e. 10 % less than in corresponding gasoline-fueled car. Specific in-use emissions (projected) in g/vkm: NOx-0.4, CO-6, methanol-1, NMHC-0.02, methane-0.02, CO_2-210. N_2O-no data.
Specific emissions based on $MJ_{methanol}$:

NOx: 400:3.05	≈ 130	$mg/MJ_{methanol}$
CO:	≈ 2000	"
MeOH:	≈ 325	"
NMHC:	≈ 7	"
CH_4:	≈ 7	"
CO_2:	≈ 69	$g/MJ_{methanol}$.

End use in urban bus. Dedicated M100-diesel engine with oxidation catalyst. Equal methanol consumption in energy terms as for diesel oil (16.6 MJ/vkm).
Specific in-use emissions (projected) in g/vkm: NOx-8, CO-2, MeOH-3, NMHC-0.02, CH_4-0.05, N_2O no data, CO_2-1145.
Specific emissions on basis of MJ methanol:

NOx: 8000:16.6 ≈ 480 mg/$MJ_{methanol}$
CO: ≈ 120 "
MeOH: ≈ 180
NMHC: ≈ 1 "
CH_4: ≈ 3 "
CO_2: ≈ 69 g/$MJ_{methanol}$.

<u>Biomass cultivation, harvesting.</u> Emissions connected with growing Salix in short rotation forest originate in manufacture of fertilizers and chemicals and use of farm tractor and truck fuels. Emissions are dealt with under ethanol (appendix 4.5; wheat). It is assumed that these are in Salix cultivation proportional to the lower energy input, which is set to 6.5 % of the biomass energy content, or 13 % on basis of methanol energy, versus 29 % for ethanol. Emissions in silviculture, see appendix 4.5.
Specific emissions per MJ methanol will thus be:
SOx: ≈1, NOx ≈70, CO ≈16, HC ≈10 mg, CO_2 ≈9 g.

<u>Transport</u> to conversion plant. Trucks with emissions as for road tankers (appendix 4.1). Energy usage 3 % of MJ methanol energy.
Specific emissions based on MJ methanol:
NOx: (15000·0.03):(0.4·35.5) ≈ 32 mg/$MJ_{methanol}$
CO: ≈ 2 "
HC: ≈ 1 "
CH_4: <<1 "
N_2O: <1 "
CO_2: ≈ 2 g/$MJ_{methanol}$.

<u>Conversion.</u> The conversion via gasification is associated with release of excess carbon in the wood over the hydrogen richer product methanol as vented gas from acid gas removal unit and as flue gas from purge gas firing and possibly wood or gas fired auxiliary boilers. Total carbon release as CO_2 is about 1.4 kg per liter methanol or 90 g/$MJ_{methanol}$. At venting of CO_2 a small amount of hydrogen sulfide is also vented, corresponding to ≤1 mg SO_2 per MJ methanol (after oxidation in the atmosphere). Firing in bolilers may be needed to supplement recovered heat in the plant to cover its energy (steam, electricty) needs. Biomass or gas combustion in auxiliary units is associated with emissions of NOx and other compounds, but no data from design studies are available. Assuming as a worst case that 12 % of the CO_2 released is from biomass combustion with the following specific emissions:
SOx: ≈25, NOx: ≈80, CO: ≈150, HC: ≈60 mg/$MJ_{biomass}$. CO_2: 90 g/MJ.
This translates to the following assumed emissions per $MJ_{methanol}$:
SOx: 0.12·90:90·25 ≈ 3 mg/$MJ_{methanol}$
NOx: ≈ 10 "
CO: ≈ 18 "
HC: ≈ 8 "

<u>Distribution.</u> Urban diesel oil in road tankers as in appendix 4.1. Energy usage 2 % on basis of methanol energy.
Specific emissions based on MJ methanol:
NOx: (15000·0.02):(0.4·35.5) ≈ 21 mg/$MJ_{methanol}$
CO: ≈ 1 "
HC: ≈ <1 "
CH_4: ≈ <<1 "
N_2O: ≈ <1 "
CO_2: ≈ 1.4 g/$MJ_{methanol}$.

APPENDIX 4.5

CALCULATION OF EMISSIONS - **ETHANOL**

Base data and transformations in the different steps of the fuel chain wheat growing to ethanol (wheat/straw case) and the chain Salix growing or silviculture to ethanol.

Cultivation, harvesting - wheat. Emissions connected with growing wheat are connected with manufacture of nitrogen fertilizers (ammonia, nitrates), other fertilizers and chemicals and with use of farm tractor and truck fuels. At the first mentioned natural gas is assumed to be feedstock and emissions are related to natural gas burning in furnaces. Additionally some N_2O and CO_2 are released at manufacture of nitric acid and calcium nitrate /86/. In the second category emissions are related to low-sulfur (≈0.1 %) oil firing. As transport fuel urban diesel oil (10 ppmw sulfur) is used for engines without catalysts. Thermal efficency ≈35 %. Specific emissions have been used for each category as follows:
NG-firing: SOx≈0, NOx≈80-180, CO≈25, HC≈40 mg/MJ_{fuel}, CO_2-56 g/MJ.
Oil- " : 50, 100 , 120, 12 " , 75 "
Tractor : 0, 12 , 2.5, 1.5 g/kWh_{work}.
" : (12000:3.6)·0.35≈1170 , 240, 150 mg/MJ_{fuel}, CO_2≈72 g/MJ.
Emissions at energy usage of 13, 5, and 11 MJ per 100 MJ ethanol /66/: SOx≈3, NOx ≈150, CO ≈36, HC ≈23 mg, CO_2 ≈19 $g/MJ_{ethanol}$.
Additionally by combining /66/ and /86/: N_2O ≈0.8 mg, CO_2 ≈4 g/MJ.

Grain drying. Fuel: Light, low-sulfur (<0.05 %) oil. 42.5 MJ/kg. Energy usage 7 % of MJ ethanol energy.
Specific emissions on basis of MJ oil used: SOx ≈0-25, NOx-70, CO≈50-180, HC-17 mg. CO_2-75 g. CH_4 and N_2O according to /86/ 2 mg and 15 mg/MJ.
Specific emissions on basis of MJ ethanol:
SOx ≈0-2, NOx ≈5, CO ≈10, HC ≈1, CH_4 <<1, N_2O ≈ 1 mg. CO_2 ≈6 g.

Transport to conversion plant. Trucks with emissions as for road tankers (appendix 4.1). Energy usage 3 % of MJ ethanol energy.
Specific emissions based on finished ethanol:
NOx: (15000·0.03):(0.4·35.5) ≈ 32 $mg/MJ_{ethanol}$
CO: ≈ 2 "
HC: ≈ 1 "
CH_4 <<1 "
N_2O: <1 "
CO_2: ≈ 2 $g/MJ_{ethanol}$.

Conversion. Emissions of CO_2 occur in the fermentation: 0.70 kg per liter of ethanol ≈ 33 $g/MJ_{ethanol}$. Further emissions occur in combustion of biomass (straw; ≈0.03 % S) in boilers. Fuel-LHV 18.5 MJ/kg dry biomass. Fuel usage 87 % based on finished ethanol (E100) energy.
Specific emissions at biomass combustion.
SOx: ≈25, NOx: ≈80, CO: ≈150, HC: ≈70 $mg/MJ_{biomass}$. CO_2: ≈90 g/MJ.
Specific emissions on basis of finished ethanol.
SOx: ≈20, NOx: ≈70, CO: ≈130, HC: ≈60 $mg/MJ_{ethanol}$. CO_2 ≈78 g/MJ.

Distribution. Urban diesel oil in road tankers as in appendix 4.1. Energy usage ≥1 % on basis of ethanol energy.
Specific emissions on basis of finished ethanol.
SOx: ≈0, NOx: ≈10, CO: <1, HC: <1, CH_4 <<1, N_2O <<1 $mg/MJ_{ethanol}$.
CO_2: 1 g/MJ.
Mass evaporative losses are assumed to be half compared to methanol but twice as reactive in the atmosphere. Thus the loss as HCE is 4 $mg/MJ_{ethanol}$.

End use in urban buses with catalyst. Equal ethanol consumption in energy terms as for diesel oil (16.6 MJ/vkm).
Specific emissions in g/vkm based on measurements on prototype buses: NOx-12.9, CO-2.0, "HC"-0.7, CH_4 and N_2O no data. CO_2-1190 g/vkm. Emissions from future buses estimated (supported by unpublished newer data) about 30 % lower, i e NOx-9.0, CO-1.5, "HC"-0.5 g/vkm.
Specific emissions on basis of MJ ethanol:
SOx: 0 $mg/MJ_{ethanol}$
NOX: 9000 á 12900:16.6 ≈ 540-775 "
CO: ≈ 85-120 "
HC: ≈ 30- 45 "
CO_2: ≈ 72 $g/MJ_{ethanol}$.

Cultivation, harvesting - Salix. Emissions connected with growing Salix as short rotation forest are dealt with in appendix 4.4. Values corrected for 55 % total product yield (ethanol and lignin) vs. 50 % in the methanol case.

Emissions in silviculture, which gives tree residues as feedstock for bio-alchols, originate in emissions from the manufacture of the small amount of fertilizers, from machinery used and from machinery for harvesting (forwarding, chipping). Emissions are estimated to be composed /Danielsson ref.57/ of 20 % from fertilizer manufacture (as for wheat above) and 80 % from machinery used (as for farm tractor above), which yields about
NOx-950, CO-195, HC-125 mg/MJ_{fuel}, CO_2-69 g/MJ_{fuel}.
Specific emissions on basis of MJ ethanol:
NOx: 950·0.054 ≈ 50 $mg/MJ_{ethanol}$
CO: ≈ 10 "
HC: ≈ 7 "
N_2O: ≈<<1 "
CO_2: ≈ 11 $g/MJ_{ethanol}$.

Transport to conversion plant. Trucks with emissions as for road tankers (appendix 4.1). Roundtrip 250 km, motor fuel energy use 1.5 MJ/100 MJ ethanol. Specific emissions:
NOx: (15000·0.015):(0.4·35.5) ≈ 16 $mg/MJ_{ethanol}$
CO: ≈ 1 "
HC: ≈ <1 "
CH_4: ≈ <<1 "
N_2O: ≈ 0.5 "
CO_2: ≈ 1 $g/MJ_{ethanol}$

Conversion. Emissions of CO_2 occur at fermentation, in the CASH-process 0.65 kg/litre of ethanol ≈ 31 g/MJ ethanol. Additional emissions occur at combustion of biogas-methane and lignin with emissions as for biogas (appendix 4.3) and biomass (appendix 4.4).

Specific emissions on basis of finished ethanol in the Salix/ Iogen-case with accounted 1.63 $MJ/MJ_{ethanol}$ lignin combustion:
SOx: ≈40, NOx: ≈130, CO: ≈245, HC: ≈115 $mg/MJ_{ethanol}$. CO_2: ≈147 g/MJ
In the tree residue/CASH-case with 0.76 MJ methane (in biogas with one third CO_2) combustion and 0.39 MJ lignin combustion per $MJ_{ethanol}$:
SOx: ≈10, NOx: ≈ 88, CO: ≈77, HC: ≈27, CH_4: ≈30 $mg/MJ_{ethanol}$. CO_2: ≈97 $g/MJ_{ethanol}$.

CALCULATION OF EMISSIONS - **RAPESEED OIL METHYL ESTER (RME)**

Base data and transformations in the different steps from rape cultivation to RME.

<u>Cultivation, harvesting.</u> The same base data are used here as in the wheat to ethanol appendix 4.5. Natural gas is used to produce fertilizers and chemicals. Diesel oil (10 ppmw sulphur) is used for tractors.
Production of fertilizers and chemicals for rapeseed requires 75 % of the energy need in the cultivation/harvesting steps, which corresponds to 0.23 MJ/MJ_{RME}. The remaining 25 %, 0.08 MJ/MJ_{RME}, will then be used by tractors. The resulting emissions will then be:

NOx: 130 · 0.23 + 1170 · 0.08 ≈ 123 mg/MJ_{RME}
CO: ≈ 25 "
HC: ≈ 21 "
CO_2: ≈ 18 g/MJ_{RME}
Additionally:
CH_4: ≈ <<1 mg/MJ_{RME}
N_2O: ≈ <1 "
CO_2: ≈ 3 g/MJ_{RME}

<u>Transport</u> to conversion plant. Trucks with emissions as road tankers (appendix 4.1). Energy usage 2 % of final energy in the rapeseed. Specific emissions based on finished RME:

NO_x: (15000 · 0.02):(0.4 · 35.5) ≈ 21 mg/MJ_{RME}
CO: ≈ 1 "
HC: ≈ 1 "
CH_4: ≈ <<1 "
N_2O: ≈ <1 "
CO_2: ≈ 1 g/MJ_{RME}

<u>Conversion.</u> Emissions mainly from biomass combustion (as in appendix 4.4) in co-generation unit:
SO_x ≈ 25, NO_x ≈ 80, CO ≈ 150, HC ≈ 60 $mg/MJ_{biomass}$, CO_2 ≈ 90 g/MJ. 0.125 MJ biomass is required to cover the energy need of 0.12 MJ/MJ_{RME} (4.5 % of electricity and 3 % of heat generated at an average efficiency of 60 %). This leads to the following emissions:

SOx: 25 · 0.125 ≈ 3 mg/MJ_{RME}
NOx: ≈ 10 "
CO: ≈ 19 "
HC: ≈ 8 "
N_2O: ≈ <1 "
CO_2: ≈ 11 g/MJ_{RME} (biomass origin)

The transesterification to methyl ester is made with methanol, the production of which contributes to emissions. Energy usage of 2 % of the final RME energy is used for the methanol. The calculations are based on the results from table 4.4.3, where methanol is produced from biomass:

	MeOH prod. mg/MJ_{MeOH}	mg/MJ_{RME}	total (el.gen.+MeOH) mg/MJ_{RME}
SOx:	4	4 · 0.02 ≈ 0.08	3+0.08 ≈ 3
NOx:	133	≈ 3	10+3 ≈ 13
CO:	37	≈ 1	19+1 ≈ 20
HC:	19	≈ 0.5	8+0.5 ≈ 9
CH_4:	<1	≈ <<1	<<1
N_2O:	<1	≈ <<1	<<1
CO_2:	102* g/MJ_{MeOH}	≈ 2°	11+2 ≈ 13°

---

*whereof 12 fossil °whereof 0.2 fossil

End distribution. Urban diesel oil in road tankers as in the previous transport step. Energy usage about 1 % of the RME energy.

NOx: (15000 · 0.01):(0.4 · 35.5) ≈ 10 mg/MJ_{RME}
CO: ≈ <1 "
HC: ≈ <1 "
CH_4: ≈ <<1 "
N_2O: ≈ <<1 "
CO_2: ≈ 0.7 g/MJ_{RME}

End use in bus with catalyst. Fuel consumption in energy terms is the same as for the urban diesel oil case, 16.6 MJ/vkm (appendix 4.1). Emissions data from transient tests are only available for light duty engines and the results are not always consistent, indicating influences from engine design. In comparison to diesel oil RME-fueled engines gave somewhat reduced emissions of CO and HC but tendency to slightly increased NOx. Particle emissions were clearly lower, formaldehyde could be somewhat higher, acetaldehyde about the same but acrolein mostly higher. Aromatics emissions were clearly lower, but data on PAH are contradictory (use of unesterified rapeseed oil higher PAH-emissions were reported). Another source reports higher ethene emissions (but indicates higher benzene emission in spite of lower total aromatics emissions). Somewhat reduced emission of methane was also indicated. A few test data from heavy diesel vehicles support the tendencies for the regulated emissions.

With this background the data of the specific emissions for the diesel oil-fueled bus (section 4.1) will be modified as given below. SOx-emissions are very low because the RME has very low content of sulfur, about 20 ppm. There are no data for N_2O.

NOx:	15-19 g/vkm	19000:16.6 ≈ 900-1145 mg/MJ_{RME}
CO:	0.5 "	≈ 30 "
HC:	0.4 "	≈ 24 "
CH_4:	80 mg/vkm	≈ 5 "
CO_2:	1270 g/vkm	≈ 76.5 g/MJ_{RME}

CALCULATION OF EMISSIONS - **HYDROGEN**

Base data and transformations in the different steps of the fuel chain water to liquid hydrogen (LH).

Electrolysis. Hydropower electricity is considered to give no emissions. Electricity from a natural gas powered combined cycle plant operating in the condensing mode is related to the emissions being discussed as limit values for recently suggested plants in Sweden. This means per MJ_{fuel}: CO_2-57g, SOx-0.4mg, NOx-30mg, remaining species of normal interest - negligible.
Thus specific emissions based on finished fuel:
CO_2: 3.73x57 ≈ 210 g/MJ_{LH}
SOx: 0.4 ≈ 1.5 mg/MJ_{LH}
NOx: 30 ≈ 110 mg/MJ_{LH}

Liquefaction. The energy use as presented in Table 3.7.1 and the above power plant emissions implies specific emissions based on finished fuel:
CO_2: 0.91x57 ≈ 50 g/MJ_{LH}
SOx: ≈ 0.4 mg/MJ_{LH}
NOx: ≈ 27 mg/MJ_{LH}

Sea transport. Fuel: Bunker C-oil, 3-3.5 %w sulfur, LHV-40 MJ/kg, carbon content ≈ 90 g CO_2/MJ. Use in big 2-stroke diesel engines with thermal efficiency of 60 %. Consumption 4x0.7 % based on energy in finished products.
Specific emissions in g/kWh_{work}: NOx-17, CO-0.3, THC-0.9. Source ref.64. CH_4-20, N_2O-5 mg/MJ_{fuel}. Source ref. 86.
Specific emissions based on finished products:
SOx: 4x30000·2·0.007:40 ≈ 40 $mg/MJ_{finished\ fuel}$.
NOx: 4x(17000:3.6)·0.6·0.007 ≈ 80 $mg/MJ_{finished\ fuel}$.
CO: ≈ 1.6 "
THC: ≈ 4 "
CH_4: 4x0.007·20 ≈ 0.56 "
N_2O: ≈ 0.14 "

Distribution. Fuel: Urban diesel oil used in road tankers equipped with catalyst. ≈10 ppmw sulfur. 35.5 MJ/liter. ≈72 g CO_2/MJ. Fuel consumption 0.4 lit./vkm. Energy usage for distribution ≤1 % of finished fuel.
Specific emissions in g/vkm: NOx-15, CO-1.0, HC-0.5, CH_4-6 % of HC, N_2O-<3 %of NOx, SOx-<0.01.
Specific emissions based on finished fuel.
NOx: (15000·0.01):(0.4·35.5) ≈ 10 mg/MJ.
CO: ≈ <1 "
HC: ≈ <1 "
CH_4: ≈ <<1 "
N_2O: ≈ <<1 "
CO_2: ≈ 0.7 "

End use in passenger car with catalyst using liquid hydrogen.
Fuel consumption ≈ 2.9 MJ/vkm.
Specific in-use emissions (projected) in g/vkm: NOx-0.1, CO-nil, HC-nil, CH_4-nil, N_2O-no data, CO_2-nil. Source: /89/ for NOx.
Specific emissions based on MJ finished fuel.
NOx: 100:2.9 ≈ 35 mg/MJ

CALCULATION OF EMISSIONS - **ELECTRICITY**

Base data and transformations in the different steps of the fuel chain electricity from power plant to traction battery.

The only emissions in this energy chain originate from the generation of electricity. The two cases studied are treated as follows.

1. Power from the generation set up in Sweden

The "renewable" part of the national electricity generation, here meaning hydro-, nuclear and wind power, gives no emissions considered in this study.
The national generation set up in Sweden produced 142 TWh_{el} in 1990 /98/. Of these 5.4 TWh_{el} (3.8 %) were based on high temperature combustion of fuels and only 3.4 TWh_{el} (2.4 %) on fossil fuels. The major part of the high temperature combustion generated electricity (5.1 TWh) came from industrial back-pressure production and only 0.3 TWh from conventional generation in the condensing mode. Of the back-pressure production 2.0 TWh_{el} originated from biomass based fuels.
The emissions from the back-pressure generation were from the allowed emission factors estimated at 3,460 tons of NOx, 4,170 tons of SOx and 2.2 million tons of CO_2. Out of these emissions 900 tons of NOx, 700 tons of SOx and 0.8 million tons of CO_2 were of biomass origin.
The emissions from the oil based condensing mode generation were from the allowed emission factors of 250 and 380 mg/MJ_{fuel} for NOx and SOx respectively and 74 g/MJ_{fuel} for CO_2 estimated at 700, 1,000 and 0.2 million tons respectively. At $\eta_{el} = 0.38$ this means per MJ_{el} produced in oil based condensing mode: CO_2-195g, SOx-1000 mg, and NOx-658mg.
The total emissions from the national generation set-up in 1990 were thus per total MJ_{el} produced: CO_2-4.3g, SOx-8.2mg, and NOx-6.8mg.

During the 1990s, beginning in 1993 and fully implemented in 1997, the allowed emission factors will be lowered. From the plans announced so far we estimate the average emission factors from fossil based (oil) electricity production in Sweden during the mid 1990s will be per MJ input fuel: CO_2-74g, SOx-100mg, NOx-100mg. In addition there are estimated to be emitted, also per MJ input fuel: CO-14mg, HC-<0.3mg, PAC et al-<10μg, part.-19mg, no data for CH_4 and N_2O.

At $\eta_{el} = 0.38$ and 5% of the electricity fossil (oil) based, the emissions per total MJ_{el} produced are: CO_2-9.7g, SOx-13mg, NOx-13mg, CO-1.8mg, HC-<0.04mg, PAC et al-<1.3μg, part.-2.5mg, no data for CH_4 and N_2O.

For each MJ_{el} in the battery we have to utilize 1.59 MJ_{el} from the national generation system and thus the specific emissions based on finished fuel are:

CO_2: 1.59x9.7 ≈ 15 g/$MJ_{batt.el}$
SOx: 13 ≈ 21 mg/$MJ_{batt.el}$
NOx: 13 ≈ 21 mg/$MJ_{batt.el}$
CO: 1.8 ≈ 3 mg/$MJ_{batt.el}$
HC: <0.04 <<1 mg/$MJ_{batt.el}$
PAC etc: <0.01 <<1 mg/$MJ_{batt.el}$
part. 2.5 ≈ 4 mg/$MJ_{batt.el}$
CH_4: no data
N_2O: no data

2. Power from natural gas

Electricity from a natural gas powered combined cycle plant producing in the condensing mode is related to the emissions being discussed as limit values for recently suggested plants in Sweden. This means per MJ_{fuel}: CO_2-57g, SOx-0.4mg, NOx-30mg, remaining species of normal interest - negligible.
For each MJ_{el} in the battery we have to utilize 1.55 MJ_{el} from a power plant, which means burning 3.10 MJ_{NG} in this case. Thus specific emissions based on finished fuel:

CO_2: 3.10x57 ≈ 177 g/$MJ_{batt.el}$
SOx: 0.4 ≈ 1.2 mg/$MJ_{batt.el}$
NOx: 30 ≈ 93 mg/$MJ_{batt.el}$

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