Life Cycle Inventory for the Golf A4

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Summary

The production inventory for the Golf is based on the development parts list. Production data on the large units was acquired directly. Many smaller parts made of one and the same material and similar technology have been summarised and placed on the inventory in accordance with their weight in kilograms. The framework of the inventory is strictly defined. Only those production processes directly involving raw materials, the car as a product, its operation and its end of life have been taken into consideration, not, however, production of the required plants and infrastructure. This inventory focuses special attention on the waste water and solid waste flows in Wolfsburg, and on the mechanical processing of the engine in Salzgitter and the gearbox in Kassel. For the first time, a comparison has been made between a petrol and a diesel engine in a vehicle which is otherwise identical.

Expenditures of energy during the production phase of the vehicle are generated primarily by the production of materials and thus from outside the automobile plants. Metallic emissions into the atmosphere and water are predominantly the result of raw material mining and material production. More sulphur dioxide and hydrocarbons are emitted during fuel production and distribution than during the later use phase.

The dominant factor during the use phase is energy demand (fuel consumption) and, accordingly, CO_2 emissions, which make up around 77% of the total value. Values have been included for expenses and waste resulting of service and maintenance.

Practises concerning used-car recycling/disposal are undergoing change. The political policies governing this issue have now been clearly defined. It is as yet unclear, however, how the Golf will be recycled/disposed of 10 or 12 years from now, since disassembly and utilisation procedures are still at the development stage.

The following table compares the Golf A4 with the Golf A3 (8.1 litre petrol/100 km) and the Lupo 3L TDI (3.0 litre diesel/100 km) and defines the changes in inventory for its overall life cycle:

Material / Energy	Golf A4	Golf A4	Golf A3	Lupo 3L	Primary Reason / Cause (A4 / A3)
	diesel	petrol	petrol	diesel	
Curb weight	1181 kg	1059 kg	1025 kg	800	Larger vehicle
Primary energy (prod.'n/use/end of life)	113 MWh	124 MWh	150 MWh	70 MWh	Lower consumption: 4.9 and 6.5 compared with 8.1 l/100 km
Steel	722 kg	634 kg	650 kg	410 kg	Heavier vehicle
Synthetics, rubber	249 kg	228 kg	170 kg	130 kg	
Aluminium	50 kg	52 kg	30 kg	130 kg	Light-weight design of Lupo 3L TDI
CO_2 emissions	27 tn	30 tn	36 tn	16 tn	Lower consumption
HC emissions	60 kg	108 kg	160 kg	40 kg	Low-level refilling losses for diesel
SO_2 emissions	29 kg	30 kg	34 kg	20 kg	Lower consumption
NOx emissions	77 kg	24 kg	26 kg	51 kg	No NOx cat for diesel
Dust/particulate matter emissions	15 kg	10 kg	8 kg	10 kg	5/0,4/2/3 kg of which are the result of engine emissions

Technical advances have proven to reduce emissions into the atmosphere and water throughout the vehicle life cycle – an achievement based on increased expenditures in the production phase. Despite significantly refined inventory methods, inventory results remain unexpectedly stable.

Contents

1 Introduction

Volkswagen initiated environmental inventories for whole vehicles in 1992. At the time, the Group's mass-volume model was the Golf A3, which is why it was selected as the object of inventory analysis. Large-scale public interest in this life cycle inventory [1, 2] and in the inventories that followed on the 3-litre Lupo [3] and the SEAT Ibiza [4] have encouraged us to examine the current-model Golf A4.

The environmental inventory is restricted to the life cycle inventory. We have refrained to date from assessing the life cycle impact, since the data needed to make any time and location-relevant impact assessments is not sufficiently available at present. Such data would include, but not be limited to, information on the duration and place or origination of impact for a range of emission types.

A comparison with other vehicles is only possible to a limited extent, because each vehicle is different from the next and inventories are becoming increasingly more comprehensive over time. For the first time, this inventory provides information on the environmental impact of motorisation through the 66-kW diesel TDI and the 55-kW petrol engine.

New information from external suppliers and the findings of dissertations by Bambl [5], Wolfram [6] and Levin [7] were included in this paper, which reflects the status as at 31 July 2000.

2 Method of Inventory

A life cycle assessment (LCA) is defined by the international standards ISO 14040/41 [8, 9]. Italic lettering identifies terminology taken from the ISO.

A product's LCA is made up of the following 3 sections:

Life cycle inventory, which records as many of the requisite types and quantities of material plus as many of the types and quantities of energy needed for the production, utilisation and end of life of a product as possible. The production of a product includes the mining and processing of raw materials. Because additional products and facilities are required for production, utilisation and end of life, a fixed scope needs to be defined. This scope determines which items are to be additionally assigned to the product in question and which are not. Such scope is referred to as the *system boundary* or inventory framework.

Life cycle impact assessment, in which the environmental categories are defined, including the greenhouse effect, ground acidification, ground eutrophication (over-fertilisation), land usage, etc. In addition, the substances recorded in the life cycle inventory are allotted an impact potential (in relation to one standard-comparison substance). The sum of the products of impact potential x the quantity of substance = the potential environmental impact of the industrial product in question within the respective environmental category.

Life cycle evaluation report, in which the potential environmental influences contained in the impact assessment are evaluated (based on their proportionate relationship to one another) using more or less subjective criteria, i.e. weighting factors, as a means of drawing conclusions and making recommendations. Moreover, it allows us to compare different industrial products in terms of their potential environmental impact.

ISO 14040 dictates that a *critical evaluation* be carried out *by independent experts*, since significant numerical errors are liable to be made given the magnitude of material and energy flow. The risk of such errors is especially high when dealing with rarely recorded emission values. On the grounds of financial and deadline considerations, no *peer review* has been undertaken.

The data contained in the 3 sections of any LCA (inventory, impact assessment and evaluation) is gathered from different areas throughout the society (see Figure 1).

The task of scientists is to examine the impact of substances contained in the atmosphere on our climate and the impact of substances contained in water and soil on the biosphere. Scientists define terms such as the greenhouse effect, hole in the ozone layer, ground acidification, ground eutrophication and land usage. In order to be able to assign measurable values to such terms, potentials are defined proportionate to reference substances. Here are some examples:

IPCC greenhouse potential (100 years) of
1 kg laughing gas (N_2O) = 320 kg $CO_{2\ \mathrm{equiv.}}$,
1 kg methane (CH_4) = 24.5 kg $CO_{2\ \mathrm{equiv.}}$.
CML ozone reduction potential within the stratosphere of
1 kg tetrachlorine carbon (CCl_4) = 1.15 kg $R11_{\mathrm{equiv.}}$ (CCl_3F)
CML ground acidification potential of
1 kg nitrogen oxide (NO_2) = 0.7 kg $SO_{2\ \mathrm{equiv.}}$

These potentials are proportionate values that lack dimension. They are used to convert a material's mass, e.g. N_2O, to the mass of a reference substance, e.g. CO_2. The purpose of such potentials is, firstly, to allow us to create weighted sums pertaining to materials which impact a defined environmental category, e.g. the greenhouse effect measured in kg $CO_{2\ \mathrm{equiv.}}$, and secondly to enable the simple appraisal of a material, e.g. 1 kg N_2O is equivalent to 320 kg CO_2 from a greenhouse perspective.

Potentials are sometimes simple to determine. The determination of ground acidification and eutrophication, for example, is based solely on chemical valences and molar masses. In some cases, however, determining potentials can be more complicated, for example determining the greenhouse potential, since the prerequisite is a global climate model. For a simple assessment of the greenhouse effect, see Enclosure 2.

The data used for the life cycle inventory is specified by the producers of materials and products, i.e. by the industry. It elates to resources and emissions. ”Engineers” develop materials, products and factories, and they, therefore, have knowledge of the required resources and the emissions generated. It is not the task of scientists to determine such data.

The data on which evaluations are based is determined by policy makers. Such data are used to draw comparisons that are not possible on a scientific basis, e.g. the acceptable increase in the fuel consumption of a car in order to achieve a reduced level of pollutant emissions with the aid of a catalytic converter.

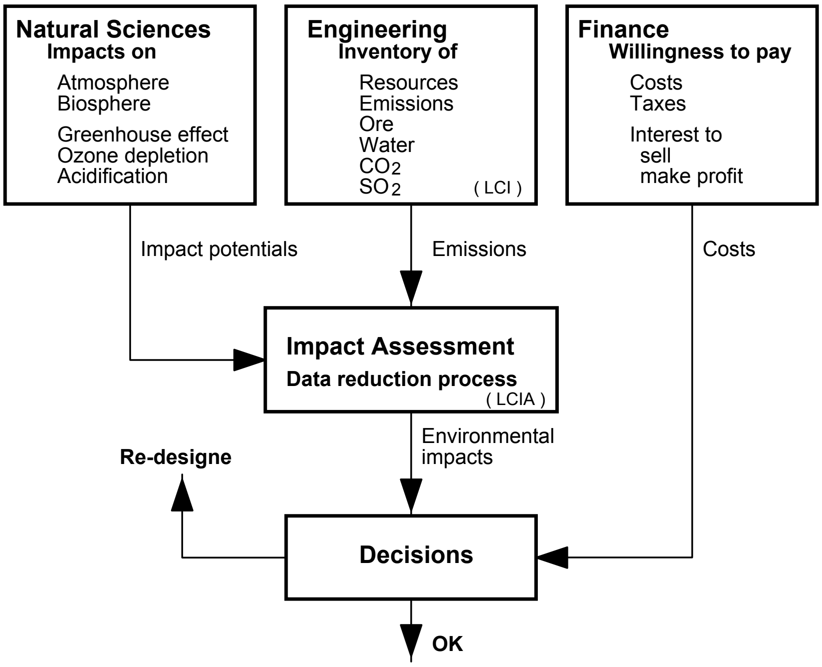


Figure 1: Data sources and flows in a LCA. The main effort consists in the data acquisition. The impact assessment is an easy mathematical step.

Knowing that the life cycle assessment of a vehicle is an extremely elaborate undertaking, we have, for the time-being, limited our efforts to compiling a life cycle inventory only.

The author has endeavoured to compile this survey in as much detail and using as much in-depth data as possible. It quickly became evident that, in some areas, the volume of available data was liable to exceed the scope of this survey and, in others, we would have to use *substitute data* taken from older models.

2.1 General Information

The object, i.e. the functional unit, of this inventory is the Golf A4, 1999 model, 4-door, with 1.4 litre 55 kW petrol engine or 1.9 litre 66 kW TDI diesel engine and a 5 speed manual gearbox, the characteristics and features of which are detailed in the product description. Some of these features are referred to in Enclosure 1.

This publication excludes extensive details, in particular with respect to comprehensive process plans and parts lists.

The scope of our inventory, i.e. the *system boundary*, is narrow by definition. Only those processes have been taken into account which are directly linked to the car as a product. This includes pre-production chains and final-product manufacturing, but not the production of machinery. (See Figure 2)

The *degree of data detail* is greatest within the VW plants. Individual components weighing at least 1 g have been taken into account. Tables on the production of materials and the generation of electric energy have been prepared in the form of completed modules, all of which are prepared in separate projects. Non-regulated substances in engine emission have been taken into consideration to the extent that they can be technically identified and measured.

	Tools Factories	**The product car**	**Service fluids Petrol/Diesel/Oil**	**Infrastructure Roads**
Administration				
Planning				
R & D			**Prospecting**	
Raw materials		**Materials**	**Crude oil**	
Production		**Suppliers** **VW Factories**	**Refinery** **Distribution**	
Use phase		**Maintenance**	**Petrol/Diesel combustion**	
End of life		**Shredder**	**Used oil**	
Disposal				

Figure 2: The system boundaries. Energy and resources are consumed in each field of the table.
Emissions into the air, water and waste occur in all fields.
The life cycle inventory only considers the shaded fields.

The *allocation* of *resources* and *emissions* during *coupled production* is individually carried out on a case-by-case basis. At the refinery and at the automobile plant, allocations are made according to mass. Each material is linked only to those resources actually used for its production. Secondary materials, therefore, will only be linked to the recycling process, but not to the processes originally involved in mining the primary materials.

2.2 Method and Terminology

The first step is to compile overview plans consisting of individual processes and sub-plans. The principal plan (see Figure 3) describes the technosphere which is embedded in the environment. The plans are further subdivided and broken down all the way to the individual processes. The result is a plan directory, quite similar to the file directories created by modern IT systems. Thus, a plan is much like a directory, a process like a file. Figure 4 depicts an excerpt from the plan directory. We have not illustrated the entire directory here, which embraces all individual plans.

The concept of plans, modules and processes enables a structured approach. Modules may be created independent of one another. And the requirement by some firms to treat processes confidentially can be complied with by summarising their sub-inventories within a module and releasing this information only.

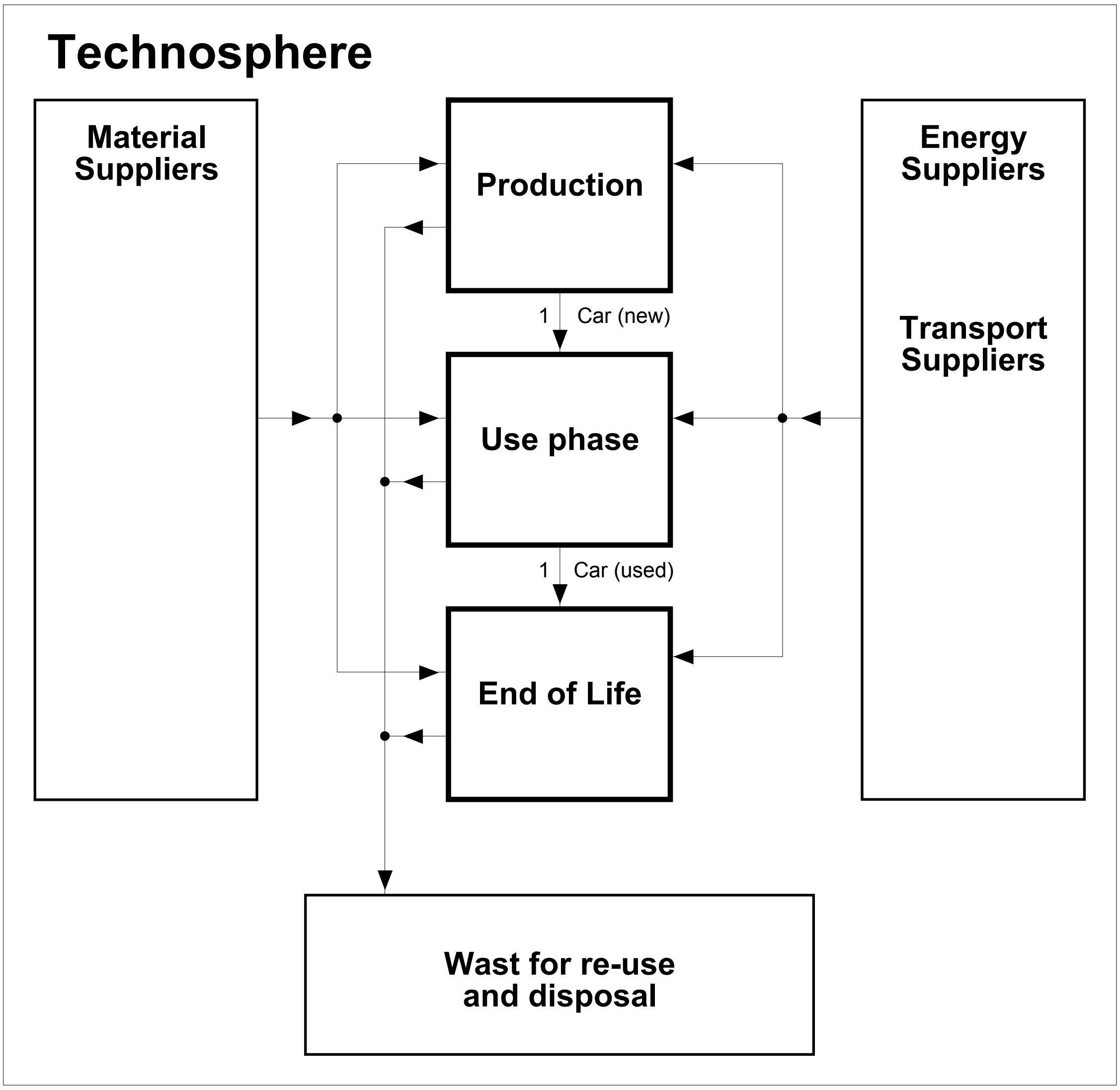
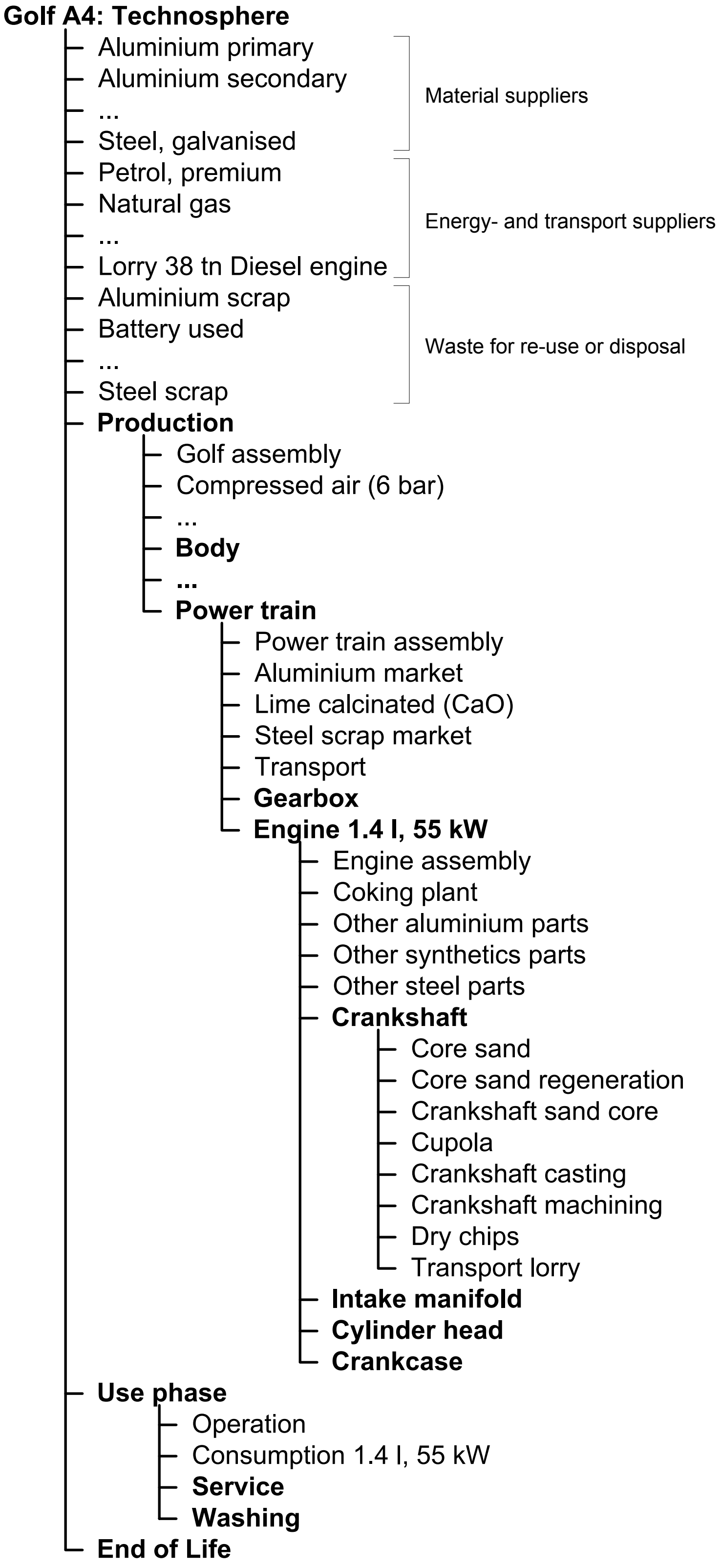


Figure 3: Scheme of the flow chart of a super ordinate inventory plan. The "Production" includes all processes in the production of the car. The "Use phase" includes operation of the car, care and maintenance. The "End of Life" includes the dismantling of the scrap car, sale of parts and shredding. The "Material Suppliers" and "Energy Suppliers" contain processes consolidated up to the resources/emissions. Material flows with no source/sink pair within a plan exceed the plan limit, and therefore land in the next higher plan. These also include secondary materials from the "Waste for re-use" block and secondary materials required in the "Material Suppliers" block.



Golf A4: Technosphere
- Aluminium primary
- Aluminium secondary
- ...
- Steel, galvanised
- Petrol, premium
- Natural gas
- ...
- Lorry 38 tn Diesel engine
- Aluminium scrap
- Battery used
- ...
- Steel scrap
- **Production**
  - Golf assembly
  - Compressed air (6 bar)
  - ...
  - **Body**
  - **...**
  - **Power train**
    - Power train assembly
    - Aluminium market
    - Lime calcinated (CaO)
    - Steel scrap market
    - Transport
    - **Gearbox**
    - **Engine 1.4 l, 55 kW**
      - Engine assembly
      - Coking plant
      - Other aluminium parts
      - Other synthetics parts
      - Other steel parts
      - **Crankshaft**
        - Core sand
        - Core sand regeneration
        - Crankshaft sand core
        - Cupola
        - Crankshaft casting
        - Crankshaft machining
        - Dry chips
        - Transport lorry
      - **Intake manifold**
      - **Cylinder head**
      - **Crankcase**
- **Use phase**
  - Operation
  - Consumption 1.4 l, 55 kW
  - **Service**
  - **Washing**
- **End of Life**

Figure 4: Excerpt from the Golf A4: Technosphere directory for administrating the plans, modules and unit processes. The path for manufacturing the crankshaft has been illustrated in detail. Plans are printed in bold type. Modules and unit processes are found at the end of the path. The inventory of a plan is a table of product inflows and outflows, specific to a selected product, e.g. 1 ”Golf A4”.

On a final note, we have provided technical IT definitions [10], below, for several terms, whereby we do not make any claim as to this being a complete listing.

Plan: A graphic representation that illustrates how processes are linked. A plan must contain at least 2 connected objects (plan, module or unit process); it may not contain isolated objects or object groups. Plans are hierarchically structured, as are directories and files. The objects contained in a plan are symbolised by named rectangles. Plans contain no data on material quantities; they do contain data on connections - symbolised by lines with directional arrows – between input and output for the objects contained in the plan.

Unit process: A table with quantified input and output products. This is where material and energy quantities are entered. Although not strictly necessary, the laws of physics, such as the conservation of mass and energy, should be observed when transforming input products to output products. The term ”unit” implies that the table of input and output products is associated with a reference product, the numeric value of which is logically set to = 1. Unit processes are symbolised within the plans by non-bold-type rectangles. Table values for linked products are entered within the rectangles. From a mathematical perspective, a unit process is a vector.

Module: A unit process within a database of global validity, i.e. it can be linked to several plans at once. It is symbolised in plans in the same way that unit processes are.

Scaling factor: The number by which a table (unit process) is multiplied so that the supply quantity (source) of a process equals the accepted quantity (drain) of the other process. Each process has its own scaling factor. Scaling factors are calculated using the plan inventory, but are not explicitly recorded in the plan. Its numerical value becomes evident in the relationship between the outer (flow) to the inner (basic) value.

Connection: The course a defined product takes when it flows from an output point to an input point. The product quantity along a given connection remains unchanged, i.e. the same quantity flows into the connection as comes out of it again at the other end. The flow (name, quantity and unit) is inscribed along the connection symbol (a line). The scaling factor can thus be discerned based on the relationship of the flow quantity to the table value (outer to inner value).

Junction: The point where multiple connections for one and the same product meet. Distributor junctions have one input and several outputs. Collector junctions have several inputs and one output. A group of distributor and collector junctions can make up a general junction. There are system junctions, symbolised by a filled point, whose inventory is determined by the system (computer), and user-defined junctions, symbolised by a circle, where the user makes an explicit data entry defining the relation between the individual flows.

Inventory: The vectorial sum of the scaled processes and sub-plans within a plan. Flows which have a source and a drain, will not appear in the inventory. The inventory of the top plan is the life cycle inventory.

2.3 Software

Data relating to unit processes were collected and compiled using Microsoft’s EXCEL 5.0, subsequent to which the unit processes were imported into the inventory program.

The majority of data on the production of materials were taken from the GaBi [11] database and incorporated into a separate, special database. This allowed us to systematically standardise a good deal of terminology and to update diverse data. Inventory processing itself was done using the TEAM [12] code, since this application enables the necessary correction work involved in compiling the overall inventory to be carried out far more quickly and because it performs an exceptionally comprehensive consistency check.

3 Plan Structure

The cradle-to-grave life cycle of a product is very complex. The effort required to present all the processes involved is infinite, which is why the processes have to be summarised into groups, especially those processes that are relatively distanced from the functional unit.

The way processes are grouped depends on the aim of the inventory. If, for example, we want to detail the ecological backpack for each individual component of a car, we need to attach to each component the duplicates of the processes pertaining to the necessary materials, types of energy and transport. The inventory would then provide a direct overview of the resources needed and the emissions for each component. If what we want, however, is an inventory for the car as a whole, it will suffice to pass on the respective material, energy and transport requirements to a supplier contained in the top plan. The inventory would then provide interesting totals for intermediate products, among them the overall transport provisions, including the corresponding fuel consumption, and the sum of all electricity requirements.

Finally, the person preparing the inventory will develop the inventory plan based on his knowledge of the manufacturing structures, e.g. classification according to VW plants [1] or to development parts lists [3]. The structure of the parts list has the advantage of being expandable according to needs, since the points at which a manufacturers parts list ends with an assembly the respective supplier's parts list continues.

The top plan is designed according to the scheme in Figure 3 and is illustrated in Figure 5. While it already presents important inventory results, notably technical flow quantities, it shows neither the resources nor emissions. The plan does not present the total quantity of some technical flows such as natural gas, electricity and transport, because the material modules have been almost entirely consolidated down to the resources. And not all material modules are contained in the top plan, since refined materials (e.g. premium steel) are part of ”production”.

Contrary to traditional inventory practises, transport services are treated as would be an item traded on the stock market. Requests for transport services are generated on a number of occasions, as are electricity demands. Such requests for transport services are collected separately, according to the type of transport. The engine used by a given means of transport requires resources and generates emissions. The reference material for engine processes is fuel, enabling a simple presentation of how many ton kilometres can be transported using one kilogram of fuel. Such calculation is based on the assumption of a typical load. The collection of all requests for transport also has an added effect: It makes apparent how little fuel is required (and how low the level of emissions can be kept).

3.1 Production

The ”Production” inventory plan, Figure 6, is structured in much the same way as the development parts list. Since this plan makes no claim to be comprehensive (as is the parts list), larger content scopes have been summarised to allow them to be treated in a report. Contrary to construction practises, we have placed importance on being able to present inventory plans on DIN A4 pages, despite the fact that larger drawings may, at times, be more distinct.

As a rule, the parts lists contain information on the material and the weight of all parts. They do not, however, contain information on manufacturing expenditures for parts. Manufacturing expenditures are separately determined or such information is provided by the supplier. Components for which no explicit information is yet available with respect to the manufacturing expenditures involved, are depicted in pale print. They are stand-ins that indicate missing data. In such a case, calculations are made using preliminary estimates based on known parts of a similar technology.

Please be aware that the processes within a plan are grouped according to logic, but not according to location, even if the terms ”Production” and ”Assembly” would suggest this. The nitrogen used to inflate the synthetics tank is externally supplied and not manufactured on site.

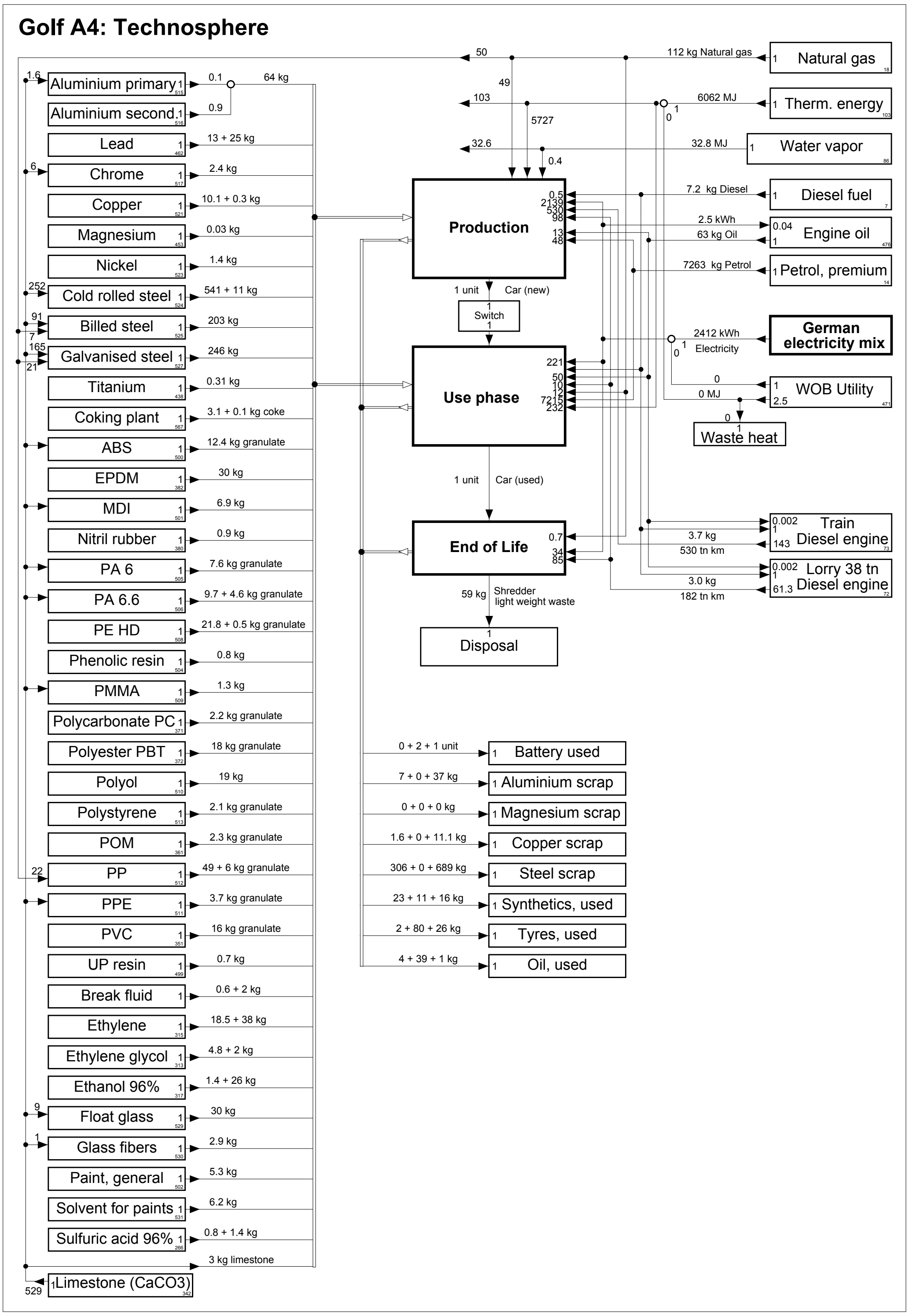


Figure 5: The super-ordinate plan for "Golf A4: Technosphere". The intermediate technical flows illustrated are already results of the inventory. The materials flow mainly into the production. Quantities for the use phase (spare parts) are specified at the 2nd position. Each of the processes, primary aluminium and secondary aluminium, deliver in a user-defined collector junction. Electrical energy is taken from the module "German electricity mix" for better comparison with previous LCI's. Modules are numbered consecutively in the database. The position is found at the bottom right-hand side for clear identification. Flows which cross over the plan boundaries are normally not shown, so that the plan remains clear.

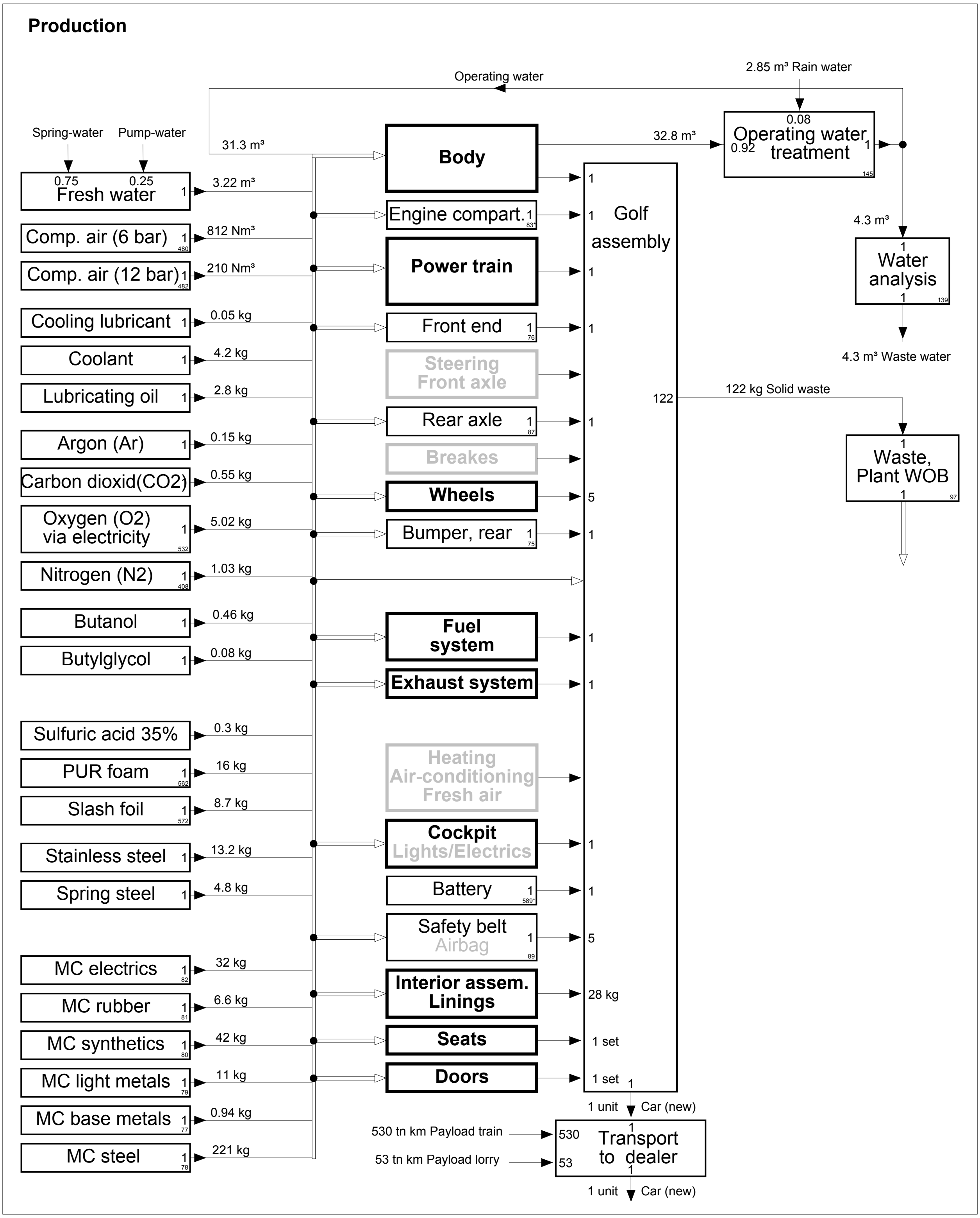


Figure 6: Inventory plan of the production phase. The Golf assembly collects the large assemblies and joins them together. The shaded in sub-plans are place holders for data which is still missing. Substitute data for the place holders are found in the material classes (MC). Process materials and assisting energy are listed here, in case they are needed in a sub-plan at a number of positions, e.g. cooling lubricant for the mechanical processing of engine and gearbox.

3.2 Use Phase

Compared to production, the use phase (Figure 7) is rather simple, since only the ”average utilisation” of a passenger car is examined. The Operation process requests the overall driving distance as well as a specific number of car washings and maintenance checks.

The ”Consumption of 1.4 l 55 kW” process contains the table showing consumption and emission as measured in accordance with the legally stipulated driving cycle. Inventory entries on car washing (Figure 8) are based on information provided by car-wash operators. Maintenance checks were designated every 15000 km, i.e. 10 checks over the entire life cycle. Request numbers for essential non-repairable parts reflect a realistic demand over the term of the life cycle. Many parts of the kind that are rarely replaced were not included.

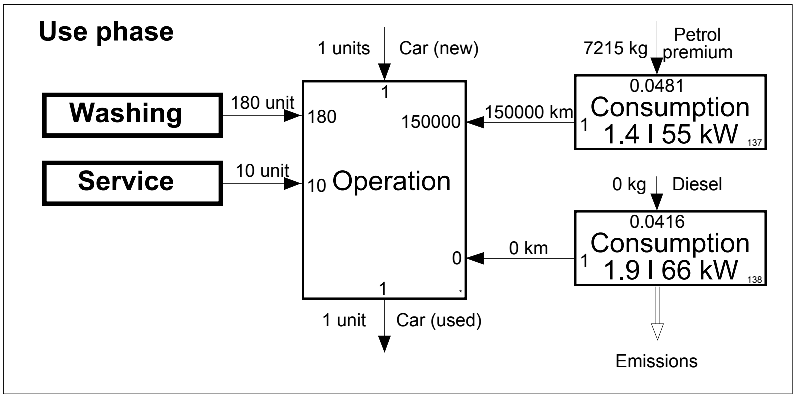


Figure 7: Inventory plan of the Use phase. The Operation process requires the driving distance and a defined amount of washings and service checks. The Consumption processes contain the tables on fuel consumption and emissions. The Operation process has a switch for petrol or diesel engine.

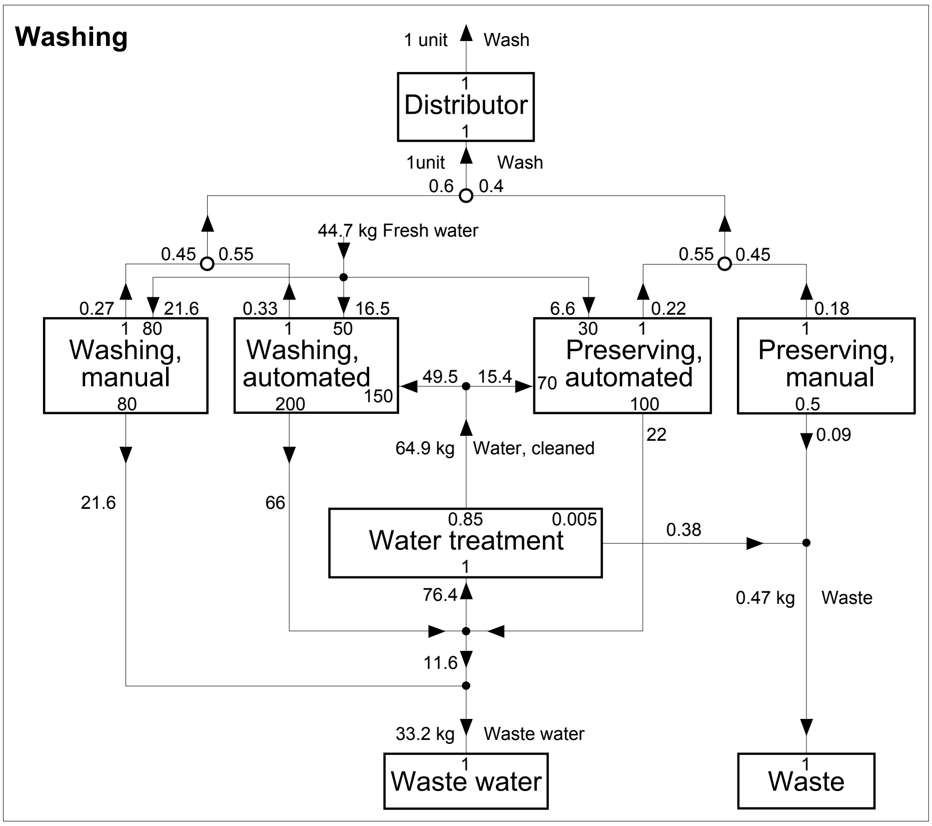


Figure 8: Inventory plan for washings. Vehicles are distributed at the 3 upper junctions. Waste water and solid waste flow to the bottom. The loops in the waste water disposal and treatment can be uniquely solved with the details in the unit processes by starting from the uppermost flow ”1 unit, wash”.

3.3 End of Life

Actual end-of-life practises for used vehicles are currently undergoing change, since disassembly and utilisation systems have yet to be developed. At this stage, it is not clear how the Golf will be recycled/disposed in 10 to 12 years from now. Figure 9 depicts the utilisation plan used. It reflects current technological standards. The cycle pertaining to recoverable waste, including metals and synthetics, has not yet been definitively closed. Accumulated ”used” materials are forwarded to a market not further defined within the scope of this inventory. The recovery of secondary materials, e.g. aluminium alloys, requires processing steps which have not been comprehensively researched for this inventory.

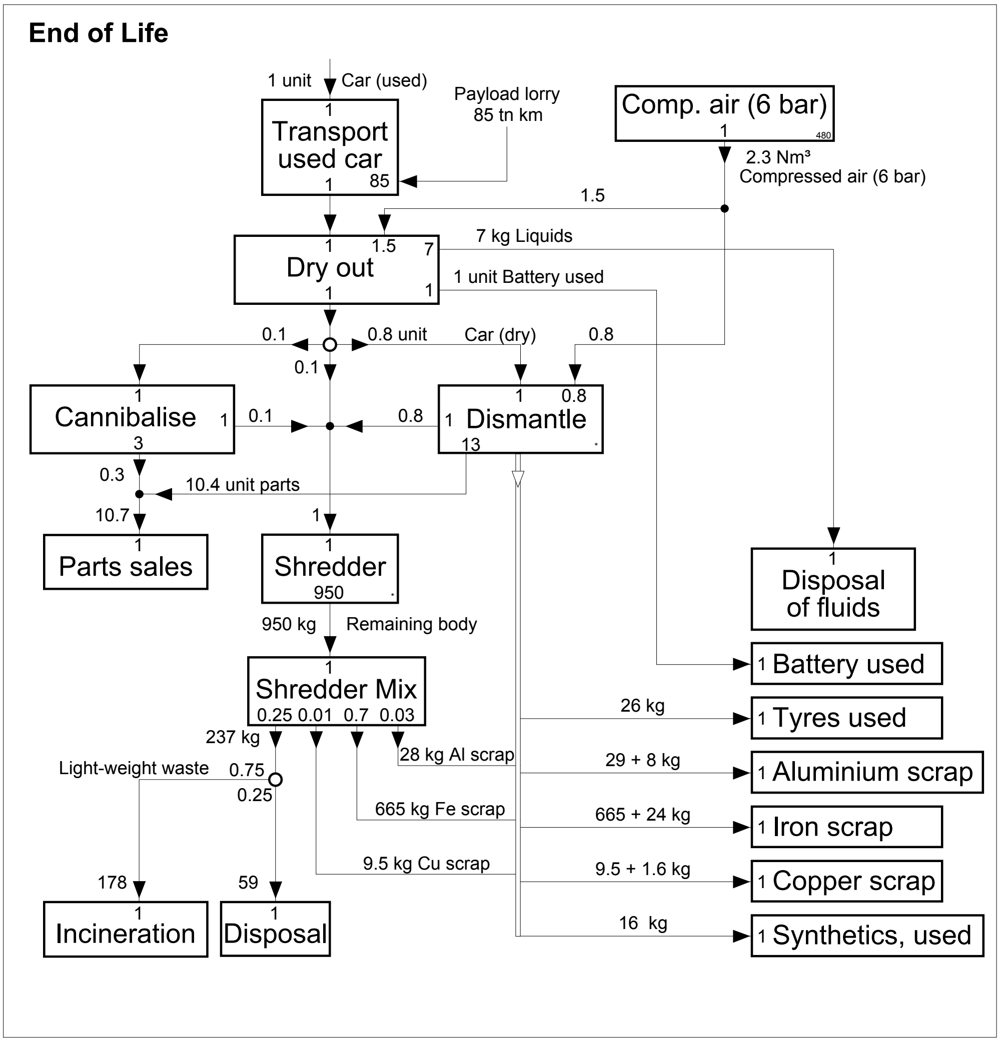


Figure 9: The End of Life inventory plan. The processes for the used materials are found in the super-ordinate plan, see figure 5. They are repeated here only for better understanding. The assumption that 70 kg are dismantled from 80% of the cars holds true for current circumstances.

4 Data Acquisition

While the majority of data for the environmental inventory was already available, it was not available in a form that allowed its direct employment. Only a small amount of data is measured specifically for the inventory, among such data the weight of tools used for the mechanical processing of the engine. Data on individual components of the Golf, the materials of which they are made and their weight is derived from the development parts list using special C++ programs. Information on the mechanical manufacturing of the engine in Salzgitter and on energy supplies, waste water and solid wastes in the Wolfsburg plant are converted to a form suitable for the inventory using EXCEL spreadsheets. The data required for the use phase is derived from measurements on consumption and emissions according in the NEDC and from new values for non-regulated emissions [13].

The total data package comprises 900 materials and products, 500 unit processes (of which 300 are database modules) and 58 plans. We have not included a listing of the unit processes in this paper.

We will now endeavour to explain how data is processed using EXCEL spreadsheets. Our example uses the mechanical processing of the engine at the Salzgitter plant and of waste water and solid wastes at the Wolfsburg plant.

4.1 General Data

The Volkswagen brand produces at multiple locations. General data (Table 1) is required for standardisation to 1 Golf unit.

Brand Volkswagen Passenger Cars, General Data	**1999**
Total number of employees	104203
Employees at the VW plant Wolfsburg	*50061*
Performance-linked wage-earners	21403
Time-rate wage-earners	10593
Salary staff	16359
Apprentices	1706
Produced units per employee	*19*
at the VW plant Wolfsburg	*12*
Daily production units at the VW plant Wolfsburg	2400
Production, Brand Volkswagen Passenger Cars	***1980601***
Lupo	89757
Polo	315500
Golf	791969
Bora	125158
Toledo	100759
Passat	420233
Alhambra	27440
Sharan	50306
Ford Galaxy	59479
Units produced at the VW plant Wolfsburg	***588835***
Lupo	89757
Bora	121957
Golf	377121
Golf, 4 doors, 1.4 l 55 kW Otto	45273
Golf, 4 doors, 1.9 l 66 kW TDI	30506
Paint surface Lupo [m²]	71
Paint surface Golf / Golf Variant [m²]	83 / 86
Paint surface Bora / Bora Variant [m²]	85 / 85

Table 1: General production data. Figures print in italics result from other figures in this table, e.g. "Production, Brand Volkswagen Passenger Cars" = Total of "Lupo" to "Ford Galaxy".

4.2 Mechanical Processing of the Engine at the Salzgitter Plant

An engine consists, among other things, of a cylinder head and a cylinder crankcase. The crankcase contains pistons, connecting rods, crankshaft, etc. Crankshaft production comprises the following steps: crankshaft blank production, preliminary processing of blank, hardening, final processing, finishing and washing. The foreman or the cost centre records both the number of crankshafts manufactured during the course of a half year and the tools, cooling lubricants and other lubricants used. The figures these records provide are the sums entered in the column headed ”Data” in Table 2. Each part and tool is weighed. The column headed ”Amount/cs_pre” (quantity per pre-processed crankshaft) will be used in the inventory as a unit process, for which application it needs to be standardised. Mass values are calculated for the individual tools and lubricants. Conversions and standardisation's are done using the formulas recorded in the column headed ”Amount/cs_pre”, e.g. ”Single-lip drill 5.0” = 100x93/(1000x183419). The ”Output” section, further down, contains some data and calculated values. ”Tool scrap”, for instance, is the sum of all tools on the input side. The ”Shavings, grey-cast iron” amount is the product of the difference in weight between the crankshaft blank and the pre-processed crankshaft multiplied by the number of blanks (all blanks are processed; only then is scrap created) minus the increased weight of the fabric insert. ”Evaporation” equals 90% of the water quantity (both types). And finally, ”Used emulsion” is the sum of all input fluids minus ”Evaporation”.

”Check formula” checks the correctness of the formulas used. The line headed ”Input” contains the sum of all input masses; ”Output” contains the sum of all output masses. If the formulas used are correct, inventory balance will be correct based on the computational conciseness of EXCEL (16 significant digits). This does not denote a mass balance as set out by the laws of physics.

Calculations on the output side are necessary, since these values are not measured at every single processing station. Used emulsion, shavings and scrap are forwarded to central entities for further utilisation.

Used emulsion from many of the processing stations at the Salzgitter plant is forwarded to the central emulsion processing unit. This unit has an overview of the overall amount of used emulsion and of the resources needed for its treatment, so that the ”Emulsion treatment” process can be balanced and scaled to 1 kg of used emulsion.

When evaluating the tables on a computer, the materials, products, tools, etc. need to be recorded in a standardised from, since a PC will tolerate no typing errors. For a PC, "CO2", "C02", "CO2 " and "carbon dioxide" are four different materials (note the capital o, the zero and the trailing blank). To avoid typing errors and variations, all names for the inventory are copied into a column and sorted into alphabetical order (where they appear once only). Those names that contain a typing error appear close to one another and can thus be detected and corrected.

Crankshaft, preparation

VW factory Salzgitter, 1sr haft year 1997. Mechanical processing, EA 111 engine. Heiko Wolfram, Sept. 1997

	Amounts/cs_pre	Data	
Input			
Work piece			
Crankshaft, blank	1.0022626 unit		9.688 kg/pc.
Tools			
Single-lip drill 5.0	5.07E-05 kg	100 pc./half-year	93 g/pc.
Graduated drill 20x14.5	1.83E-05 kg	20 pc./half-year	167.8 g/pc.
Graduated drill 20x15.1	3.026E-05 kg	30 pc./half-year	185 g/pc.
Match plate 702936-1	7.16E-05 kg	2861 pc./half-year	4.59 g/pc.
Match plate CNMG 120412 CPX	1.904E-05 kg	400 pc./half-year	8.73 g/pc.
Match plate RCMT 1204M0 CPX	5.153E-05 kg	1700 pc./half-year	5.56 g/pc.
Match plate TCMT 110208-UM	9.732E-07 kg	50 pc./half-year	3.57 g/pc.
Match plate TCMT 16T312 LF	3.386E-05 kg	1800 pc./half-year	3.45 g/pc.
Match plate TMMG 160408	3.227E-05 kg	950 pc./half-year	6.23 g/pc.
Match plate TPC 25	2.188E-05 kg	600 pc./half-year	6.69 g/pc.
Match plate WNMG 080412 MG KC	2.99E-05 kg	600 pc./half-year	9.14 g/pc.
Reversible carbide tip E-17640	1.264E-05 kg	300 pc./half-year	7.73 g/pc.
Reversible carbide tip SK 2082R00	1.638E-05 kg	400 pc./half-year	7.51 g/pc.
Reversible carbide tip SP 8793	6.288E-06 kg	258 pc./half-year	4.47 g/pc.
Reversible carbide tip VBMT 160412	1.824E-05 kg	430 pc./half-year	7.78 g/pc.
Cooling lubricants			
Fabric insert, new	0.0050771 kg	931.24 kg/half-year	
Grotanol SR 1	0.0043572 kg	0.74 m^3/half-year	1080 kg/m^3
Microgrind M3753	0.0929134 kg	16.84 m^3/half-year	1012 kg/m^3
Water (hard)	1.7795321 kg	326.4 m^3/half-year	1000 kg/m^3
Water (condensate)	1.1863547 kg	217.6 m^3/half-year	1000 kg/m^3
Lubricants			
Bed track oil	0.0038164 kg	700 kg/half-year	
Bed track oil 220	0.0087505 kg	1605 kg/half-year	
Hydraulic oil HLPD 46	0.0558339 kg	10241 kg/half-year	
Fast cutting oil	0.0269111 kg	4936 kg/half-year	
Spindel oil CLP 5	0.0019627 kg	360 kg/half-year	
Licocut C	0.0284267 kg	5214 kg/half-year	
Energy			
Electricity	16.549256 kWh	3035448 kWh/half-year	
Output			
Crankshaft, semi-finished	1 unit	183419 pc./half-year	8.447 kg/pc.
Scrap, crankshaft	0.019112 kg	415 pc./half-year	
Fabric insert, contaminated	0.0406289 kg	7452.12 kg/half-year	
Used emulsion	0.5195606 kg		
Shavings, grey-cast iron	1.208256 kg		
Evaporation	2.6692982 kg	90 %	
Tool scrap	0.0004139 kg		

Check formulas	Input	12.90427 kg/cs_pre
	Output	12.90427 kg/cs_pre
	Difference	1.78E-15 kg/cs_pre

Table 2: Sample of data preparation in the mechanical processing of the engine. The ”Crankshaft, blank" comes from an external supplier. The ”Crankshaft, semi-finished” is then hardened.

4.3 Gearbox Production at the Kassel Plant

The production of gearboxes at the Kassel plant has been newly inventoried [7]. The method of data acquisition applied is similar to that used for the inventory of the engine at the Salzgitter plant.

A gearbox consists of the following groups of components: housing, input shaft with wheels, output shaft, differential, shift components and purchase parts. The clutch on the input side and the propeller shaft on the output side are not part of gearbox production.

Among other items, the Kassel plant manufactures 6 different types of gearbox as well as engine blocks. Therefore, several allocations, i.e. arbitrary allotments of shares of energy and emission, need to be made in the inventory for the ”020” gearbox. The foundry workshop (housing) and the hardening shop (steel parts) carry out such allocations based on mass. The usage of room heating and electricity for lighting is shared according to workshop space.

4.4 Energy Supply at the Wolfsburg Plant

Energy consumption is an important cost factor. At the Wolfsburg plant, registration thereof is in the hands of the Energy Management and Utilities Technology division. Meter readings are summarised in an annual account (Table 3). It is not possible to assign precise levels of energy consumption to individual vehicle models, so that the data entered into the inventory is the average energy consumption at the Wolfsburg plant per vehicle. In the inventory for the Golf A4, annual usage amounts are linked to the production units at the Wolfsburg plant (Table 1) and allocated to the respective modules.

	Ass. lines	**Paint shop**	**Body shop**	**Mech. proces.**	**Synth parts 1**	**Synth parts 2**	**Trim pieces**	**Seats**	**Doors Cockpit**	**Press shop**	**Wheels**
Oxygen [kg]	109	1410	22478	413	371	0	4940	0	0	12942	5872
Acetylene [kg]	10	181	1825	17	34	0	237	0	0	508	988
Nitrogen [tn]	0	0	0	73	0	0	0	0	0	0	0
Carbon dioxide [tn]	0	0	152	3	0	0	47	0	0	0	123
Natural gas [tn]	0	16772	0	898	0	800	0	0	0	160	285
Drinking water [1000 m^3]	218	1130	141	76	45	56	79	9	5	60	46
Operating water [1000 m^3]	1929	1939	1797	2123	1089	1855	1835	187	12	4711	922
Tech. heat [1000 GJ]	10	67	0	5	6	2	1	1	0	0	21
Room heat [1000 GJ]	230	707	326	170	84	113	172	45	10	109	61
Comp. air 6 bar [Mio. Nm^3]	41	94	102	24	7	13	42	2	0	121	5
Comp. air 12 bar [Mio. Nm^3]	1	28	50	0	3	2	20	0	0	8	9
Electricity [GWh]	86	198	112	82	20	45	45	5	1	67	20

Table 3: Energy supply to the individual Cost Centres of the VW plant Wolfsburg, 1999.

4.5 Waste Water and Solid Waste at the Wolfsburg Plant

The Wolfsburg plant is situated in a region with poor supplies of water. Since its founding in 1938, therefore, the onus has been on keeping the consumption of drinking water down, for which purpose plans and controlling stations are in use. By introducing ”operating water”, i.e. process water circulated within the plant, the consumption of fresh water has been reduced to a minimum. Figure 10 clearly depicts the flow of water. The amount of operating water circulating within this flow is approx. 6 times the amount of waste water deposited into the Aller creak.

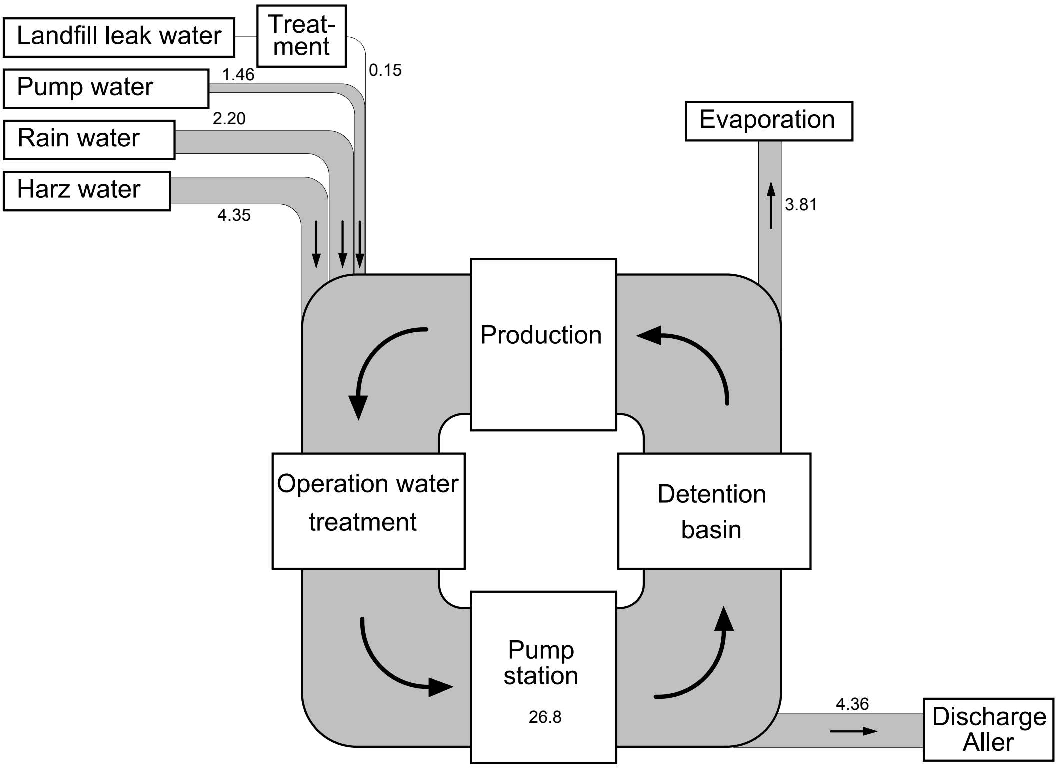


Figure 10: Water circulation in the VW plant at Wolfsburg. Figures given in Mio. m³, 1999. The recirculated stream of operation water is large. The operation water is used approx. 6 times until it is discharged to the Aller creak. Rain water is collected on the plant side, it amounts up to 1/3 of the total water input.

The plan depicted in Figure 11 details the course the water takes. The centrepiece of this water management system is the operating-water detention basin. It consists of several ponds with a combined holding capacity of 1.5 million m^3. The ponds help balance out seasonal fluctuations in the amount of water intake (especially rain water).

Landfill leakage water comes from nearby VW depots. It is delivered by lorries, cleansed using special technology and then added to plant waste water.

The waste water generated by the plant from its sanitary, production and power-station facilities is separately managed, pre-cleansed and finally purified at the Sewage Treatment Plant West. The circulating operating water is used primarily for cooling purposes in production.

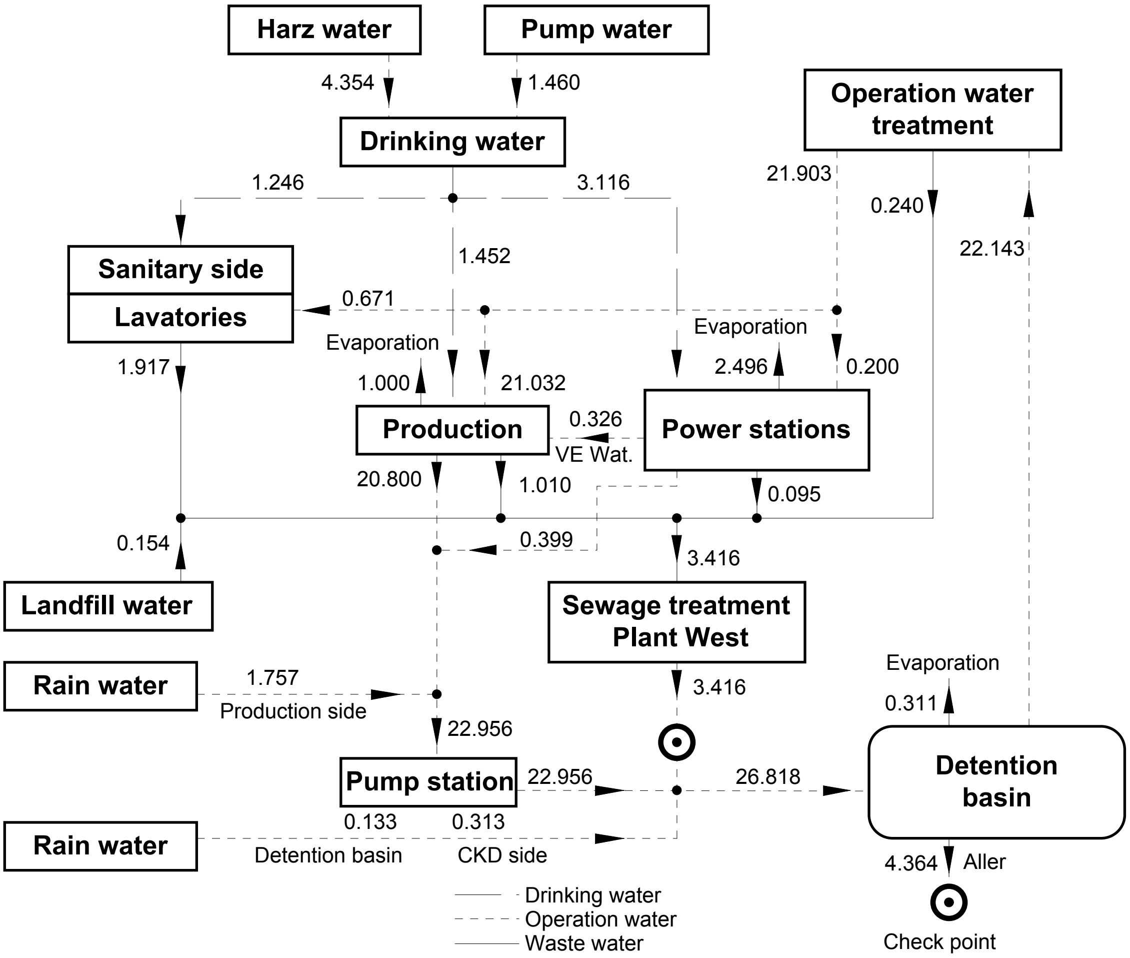


Figure 11: Water circulation scheme in the VW Plant at Wolfsburg. Figures are in Mio. m³, 1999. The operation water is used approx. 6 times until it is discharged to the Aller creek. Industrial and sanitary waste water is separately collected and cleansed in the Sewage treatment Plant West.

Data is routinely collected on water consumption and water analyses. In this area, too, strict differentiation is made between data and subsequently calculated values. Data may be used once only so that, in the event of a correction, all subsequent values will be automatically re-computed. Table 4 contains the flow-through quantities at the Sewerage Treatment Plant West and the quantity discharged into the Aller creek. It also provides information on the average waste water analyses.

A considerable portion of the fresh water is supplied to the regional power station in Wolfsburg, where it is evaporated for cooling. Since all the electrical energy contained in this life cycle inventory is procured from an alternative German supplier, the Wolfsburg power station is excluded from the water circulation as depicted in Figure 11. Sanitary facilities and depot waste water has also been excluded, on the grounds that both these areas do not fall within the inventory scope. Figure 11a depicts the cycle as it is ultimately included in the inventory.

The exclusion of sanitary water cycles and power plants not only alters the amount of waste water, but also the analysis values. In the inventory, only the waste water quantity is altered, not the analysis value. We have also refrained from apportioning rainfall to the various areas, allocating instead the overall amount of rainfall on the plant grounds to production.

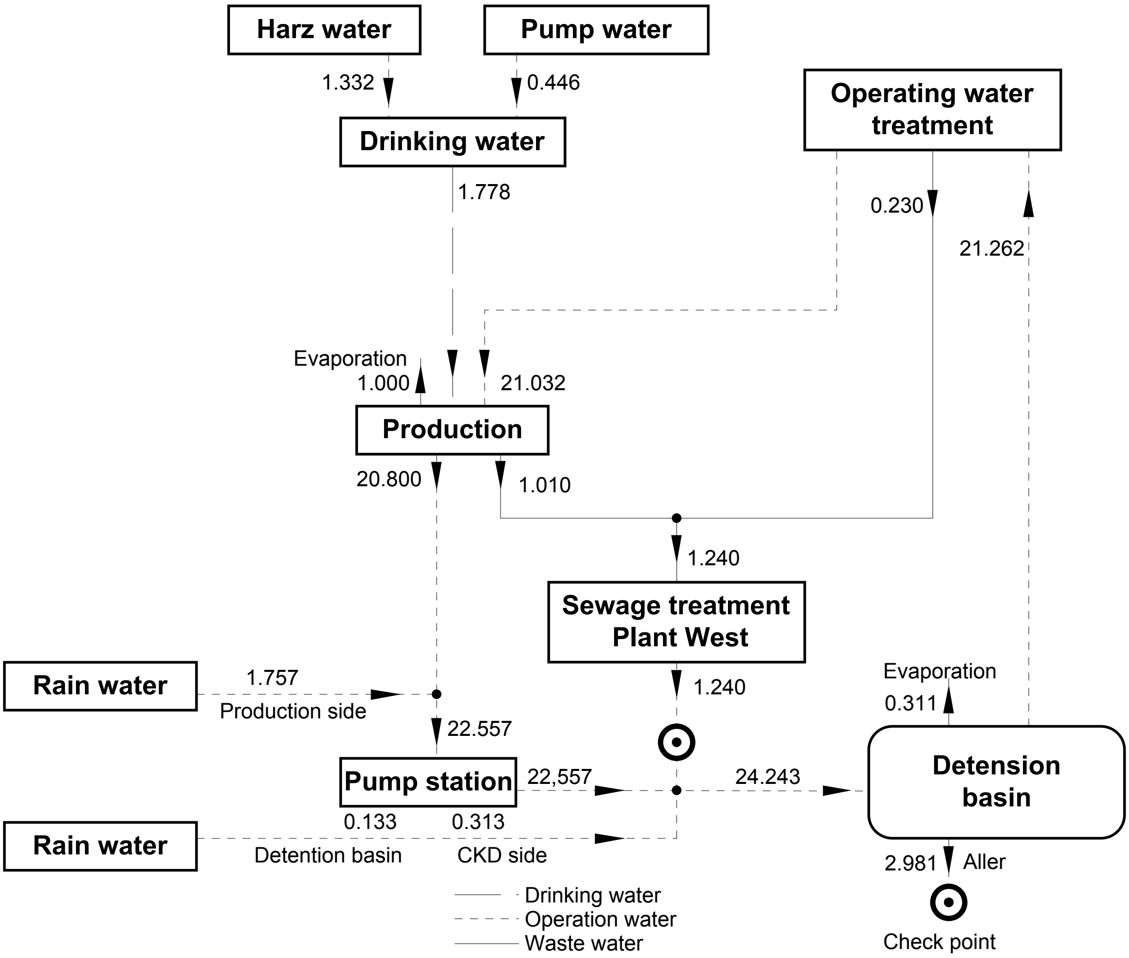


Figure 11a: Water circulation scheme as used in the inventory. It results from the scheme in figure 11 by taking out the flows from the Power station, sanitary side and landfill leakage water. The water flows through the "Production" are kept constant, they determine the rest of the flows. Figures are given in Mio. m³, 1999.

Data precision hinges on the measuring method applied. Directly measurable indicators are normally more precise than those measured indirectly. One example of a directly measured indicator is the value denoting a given quantity of paint sludge. Paint sludge is more or less constantly generated and collected in a tank and weighed. Indirectly measured values are obtained quite differently. Take, for instance, the pollutants contained in waste water. While the waste water volume is continually registered, the amount of pollutants it contains is calculated based on waste water analyses carried out once a month. The monthly waste water volumes deposited into the Aller vary between 0.16 and 0.80 million m^3/month. Random COD-value samples range from 21 to 50 mg O_2/l. To calculate the COD value for the inventory (total volume in 1999 per Golf), we can either take the annual waste water volume for 1999 and multiply it by the annual COD average or we can take the monthly waste water volumes, multiply them by the monthly-analysis COD values and add together all the resulting monthly values. These methods of calculation differ by 11%, which is our reference value for COD-value fallibility. For other forms of pollutant, including those contained in waste gases, the degree of fallibility can be even greater (e.g. up to 20% fallibility for nitrate).

Substance	Unit	Limit	Check point Sewage plant	Check point Aller
Flow in 1999	Mio m³		3.416	4.364
Temperature	°C		21.6	15.5
pH-value		6.5 - 9.5	7.22	8.44
Conductivity	µS/cm		1479	799
Carbonate	°dH			8.01
Opacity	TE/F		24	
Ammonia-Ions (NH_4^+)	mg N/l	4	0.3	0.10
Adsorbable organic halogens (AOX)	µg Cl/l	100	51	35
Barium (Ba)	µg Ba/l	2000	33	
Benzene (C_6H_6)	µg/l		0.25	
Lead (Pb)	µg Pb/l	50		2.8
Biochemical oxygen demand (BSB5)	mg O_2/l	15	7.9	5.0
Cadmium (Cd)	ng Cd/l			173
Calcium (Ca)	mg Ca/l			82
Chlorides (Cl^-)	mg Cl/l	500		109
Chromium (Cr)	µg Cr/l	500	21	2.5
Chemical oxygen demand (CSB)	mg O_2/l	60	92	33
Dichlormethane (CCl_2H_2)	ng/l		30	
Iron (Fe)	µg Fe/l			155
Ethyl benzene ($C_6H_5C_2H_5$)	µg/l		0.38	
Hydrocarbons	µg/l	5000	475	
Copper (Cu)	µg Cu/l		11	12.7
Magnesium (Mg)	mg Mg/l			11.4
Nickel (Ni)	µg Ni/l	120	76	49.4
Nitrates (NO_3^-)	mg N/l		4.7	1.7
Nitrites (NO_2^-)	µg N/l	1000	128	44
Phosphorus, total (P)	µg P/l	1000	1510	560
Mercury (Hg)	ng Hg/l			67
Oxygen (O_2)	mg/l			11
Sediments	mg/l		421	6.6
Nitrogen, total (N)	mg N/l	10	5.2	1.8
Sulphates (SO_4^{--})	mg SO_4/l	300		123
Tetrachlorethene (C_2Cl_4)	µg/l		1.02	
Tetrachlormethane (CCl_4)	ng/l		30	
Total organic carbon TOC	mg/l			15.9
Toluol ($C_6H_5CH_3$)	µg/l		1.0	
1,1,1-Trichlor ethane ($C_2Cl_3H_3$)	ng/l		30	
Trichlor ethene (C_2Cl_3H)	ng/l		58	
Trichlor methane (CCl_3H)	ng/l		30	
m/p-xylol [$C_6H_4(CH_3)_2$]	µg/l		0.48	
o-xylol	µg/l		3.5	
Zinc	µg Zn/l	500	128	47

Table 4: Waste water analyses at the check points "Sewage plant" and "Discharge into the Aller" in Figure 11. The concentration values are averages of the monthly probes taken in 1999.

Table 5 exemplifies how data on waste is acquired. The table is a record of the waste transport departures from the plant gates. The waste categories are set out in the European Waste Catalogue. The table contains major items only.

It is not possible to allocate the data from Tables 4 and 5 to the individual vehicle models. In the inventory, this data is linked to the production units at the Wolfsburg plant (Table 1).

Solid waste, Wolfsburg plant		**1999**	**1999**
Metallic waste for recovery	**EWC-Code**	**Amount [t]**	**Amount [kg/car]**
Iron scrap	170405	34744	59,00
Electrical cables	170408	1232	2,09
Aluminium scrap	120103	1050	1,78
Base metals scrap	120103	195	0,33
Industrial waste for recovery			
Paper, cardboard	150101	6712	11,40
Wood	150103	4603	7,82
Synthetics, used	120105	3663	6,22
PVC waste	120105	358	0,61
Electronic scrap	160205	302	0,51
Plastic foils	150102	388	0,66
Industrial waste for disposal			
Packaging	150106	4183	7,10
Household similar waste	150106	3249	5,52
Synthetics, used	170203	1944	3,30
Wood	150103	1122	1,91
PVC waste	120105	247	0,42
Toxic waste for recovery			
Paint residues	080107	1810	3,07
Used oil	120107	1640	2,78
Solvents	070704	512	0,87
Grinding sediments	120111	585	0,99
Toxic waste for disposal			
Paint residues	080107	211	0,36
Excess sediments	190201	2725	4,63
Hydroxide sediments	190201	1702	2,89
Oil separation sediments	130502	343	0,58
Phosphate sediments	110108	360	0,61
Transformators, Condensators	160201	322	0,55

Table 5: Solid waste data is transformed from quantity/year to quantity/car using general data from table 1. The units produced (588 835) in the VW Plant Wolfsburg are taken as reference. Stamp scrap from the press shop is returned to the steel supplier, this scrap is excluded from the table.

4.6 Suppliers

Some suppliers, e.g. of batteries, tyres and small steel parts, manufacture similar parts in a variety of sizes, supplying multiple automobile manufacturers. This means it is not possible – for reasons of allocation - to create an inventory for special Golf parts. In such a case, the supplier provides a ”partial, weight-based inventory” (e.g. 1 kg batteries or 1 kg tyres) in addition to the weight of the part delivered to Volkswagen.

Commercially available tables are used for material mining and production.

4.7 Use phase

The items contributed to the inventory by the use phase are, essentially, the production and consumption of petrol and engine oil, but also of coolants, brake fluid, windscreen cleaning fluid and tyres. Expendable parts, such as spark plugs, oil filter, battery, bumpers, etc., are replaced during maintenance checks.

How much fuel a passenger car consumes and, thus, the pollutants it emits depends on the style of driving. Lawmakers have prescribed driving cycles, according to which fuel consumption and exhaust emissions are to be measured, e.g. the New European Driving Cycle (NEDC) in Europe and the US City and Highway Driving Cycle in the USA. Some institutions, among them the Germany automobile association *Allgemeine Deutsche Automobil Club* (ADAC), believe that these driving cycles are not representative, which is why they use their own driving cycles to determine consumption.

The following figures are a measure of how driving-style-related fuel consumption data varies:

	55 kW Otto	66 kW TDI
US City	6.0 l/100 km	5.0 l/100 km
NEDC	6.5 l/100 km	4.9 l/100 km
ADAC	8.1 l/100 km	5.9 l/100 km

This inventory uses the NEDC test figures.

The data on pollutant emissions contained in our inventory has been ascertained using no other sources than the legally stipulated driving cycles and measuring regulations mentioned above. The inventory uses NEDC fuel consumption figures and the regulated components CO, HC and NO_X. The values for non-regulated pollutants (PM, SO_2, SO_4^{--}, N_2O, PAH) are not available for the current-version Golf. We have used, instead, substitute data [13] on the Golf, measured using the US City driving cycle. This data is deemed to be representative of modern petrol engines with a three-way catalytic converter and of diesel engines with an oxidising catalyst. The data contained in Ref. [14], and still used in the ”Life Cycle Inventory of a Golf” [1], is outdated.

Oil and brake fluid quantities are established based on the prescribed maintenance intervals. The same applies to consumables such as oil, air, fuel and pollen filters, spark plugs, and wiper blades. According to VW customer service, every car averages one new bumper during its life cycle.

Data on tyre production is obtained from the supplier. The average running distance of tyres was fixed at 43000 km. Dust emissions were calculated based on tread wear and tyre dimensions.

The battery consists of a polypropylene casing, lead - lead-oxide and 25% sulphuric acid. Its service life was fixed at 4 years.

Expenditures for washing and paint work care were established by questioning car wash operators. Figure 8 illustrates the process involved.

This inventory does not take expenditures and wastes relating to vehicle workshops into account. The assumption is that this source of waste is one not to be neglected.

5 Results

This life cycle inventory brings to light specific aspects relating to the passenger car, including:

- the vast number of materials specially developed for the automobile industry,
- the large number of individual components which make up a passenger car,
- that energy is consumed primarily in the use phase,
- that only few pollutant emissions (CO_2, NO_x) are predominant in the use phase,
- the high rate of recycling.

The general results for the overall vehicle are set out below, as are a number of selected individual results.

5.1 General Results

The cumulative weight distribution of the individual components (Figure 12), calculated using the data contained in the development parts list, shows that the 80 heaviest parts make up just half of the vehicle's weight. The heaviest "component" is the fuel in the tank (46 / 42 kg), followed by the cylinder crankcase (42 kg) in the diesel or the 5 tyres (30 kg) in the petrol model. The body-in-white consists of numerous individual panels, the heaviest of which are the roof (12 kg) and a side panel (11 kg). The final 3% of the total weight is made up of several thousand individual components such as screws, pins, clips, springs, connectors, seals, etc. The weight of most components was calculated by the respective design engineer so as to be able to keep track of weights. Though this is difficult to do for some components, for example paint, the total weight so determined per individual component does correspond with the true vehicle weight, give or take a few kg. The weight of individual components was balanced off against dismantling research.

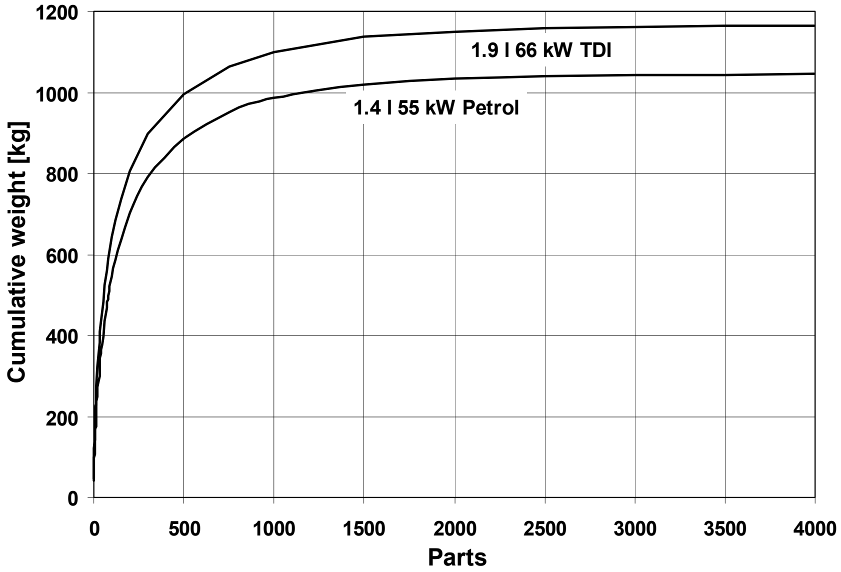


Figure 12: Cumulative weight distribution of parts of the Golf A4 with Otto and Diesel engine
The heaviest parts are:
A4-Otto: Petrol in the tank (42 kg), tyres (30 kg), well-base rim (18 kg)
A4-Diesel: Diesel in the tank (46 kg), crankcase (42 kg GCI), tyres (34 kg)

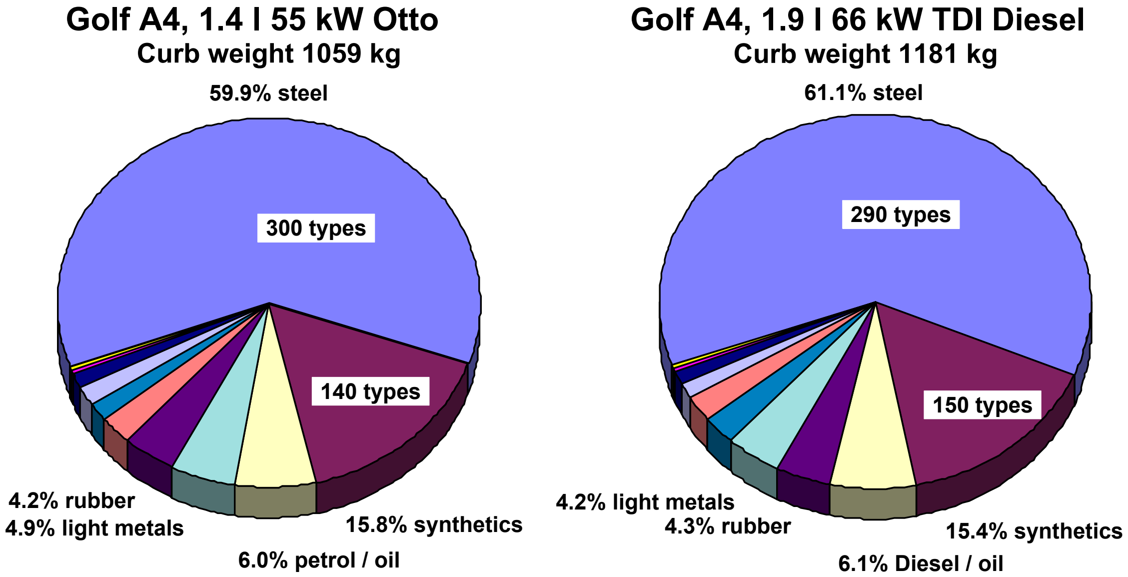
The materials pie graph, Figure 13, is based on the parts list data. We can identify no preferred material - neither among the large nor the small components. The materials group "steel" dominates overall. The large number of different types of steel is indicative of how specialised this material is.

The second group, synthetic materials, poses a definition problem, for the vast majority of synthetics consist of material mixtures, e.g. fibre-glass-reinforced polyamide PA 6.6 – 30% GF or PVC – plastisol comprising 25% binder (PVC), 30% softener (DINP) and 45% filler (chalk). For the purpose of weight classification, however, no distinction is made between synthetic components, i.e. both the plastisols and fibre-glass-reinforced synthetics are allocated to the synthetic materials group.

The only light metal used is aluminium alloy, and the share thereof is conspicuously low. These components are cast using 100% recycled aluminium (AlSi9Cu3).

Cables, electric motors, switches, fuses, etc. are combined into a single materials group (”electrical components”).

The sum of all non-ferrous metals (lead, chrome, copper, titanium) does not correspond with the information as set out in Figure 5, since the copper contained in electric motors and cables, and the lead in batteries are allocated differently.



	Golf - 1.4 l 55 kW Otto		Golf - 1.9 l 66 kW TDI	
Material	**Mass [g]**	**Share [%]**	**Mass [g]**	**Share [%]**
Steel and iron	634392	59.9	721805	61.1
Synthetics	167465	15.8	182270	15.4
Fuel / oil / lubricants	63989	6.0	71537	6.1
Light metals	51832	4.9	49920	4.2
Tyres and rubber	44124	4.2	50465	4.3
Glass	30095	2.8	30095	2.5
Electric motors, cables	24944	2.4	25213	2.1
Base metals	19430	1.8	26986	2.3
Insulation	16260	1.5	16435	1.4
Paints	4156	0.4	4156	0.4
Others	2113	0.2	1854	0.1
Total	**1058800**	**100**	**1180736**	**100**

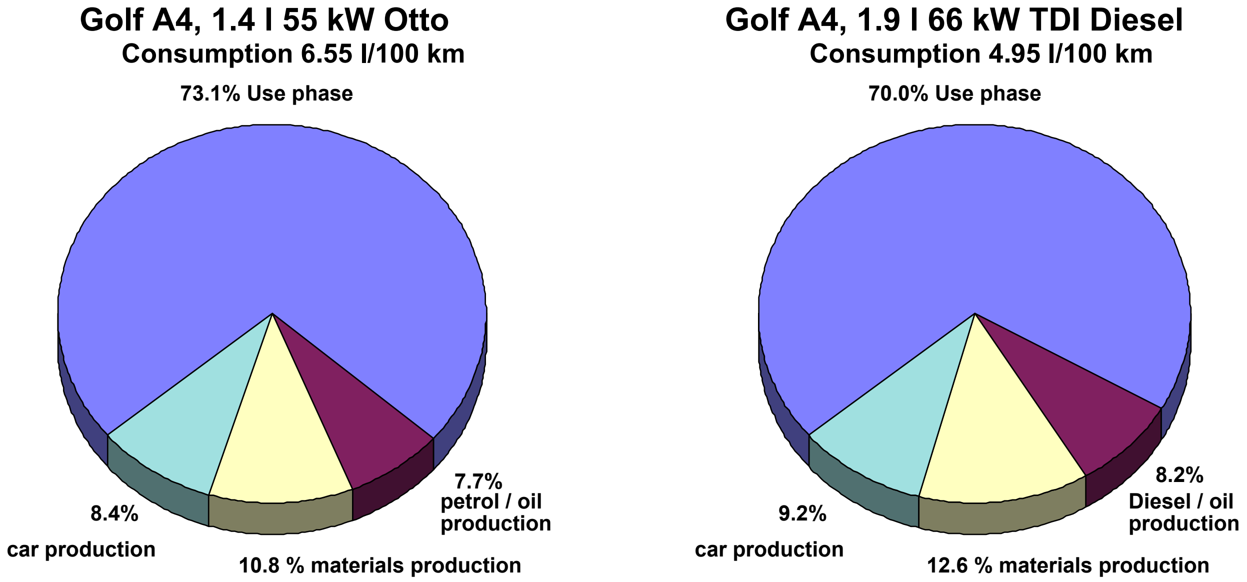
Figure 13: Distribution of materials. Steel contains base metals, e.g. titanium and chromium, as alloy components. Light metals are mainly aluminium alloys. Synthetics contain mineral fillers and reinforcing fibres. Electronic components are summarised in the group "Electric motors, cables". Reinforcements (steel and textiles) in the tyres are included in the group "Tyres". The large number of steel and synthetics types result from design requirements.

	55 kW Otto	**66 kW Diesel**
Consumption [l/100 km]	6.50	4.95
CO_2 [g/km]	153	132
CO [mg/km]	101	101
NM VOC [mg/km]	43	15
NOx [mg/km]	13	377
CH_4 [mg/km]	9.7	5.6
N_2O [mg/km]	39.4	10
SO_2 [mg/km]	9.2	7.9
SO_4^{2-} [mg/km]	0.7	0.6
Particulate matter [mg/km]	2.4	30
PAH [µg/km]	13	2

Table 6: Consumption and emissions during the operation of a Golf with 55 kW Otto and 66 kW Diesel engine.
Values measured by the NEDC are listed here. Figures for non-regulated emissions are taken from substitute data [13], measured by the US-City Driving Cycle. These are subject to the composition of the fuel used. The density of the petrol (premium) and Diesel fuel used here was 0.74 and 0.84 kg/l and the sulphur content was 100 ppm.

Fuel is consumed, i.e. burned, during the use phase. This generates a whole range of pollutants which are produced in small quantities and some of which are listed in Table 6.

The expenditure of energy is a consequence of fuel consumption, fuel production, and the production and processing of materials (see Figure 14). The end-of-life phase was not included because the expected amount of recovered energy from the calorific value of the materials far outweighs the expenditure of energy for dismantling and shredding.


Golf A4, 1.4 l 55 kW Otto
Consumption 6.55 l/100 km

Golf A4, 1.9 l 66 kW TDI Diesel
Consumption 4.95 l/100 km

Total primary energy consumption (Otto/Diesel) for 150000 km, 10 years

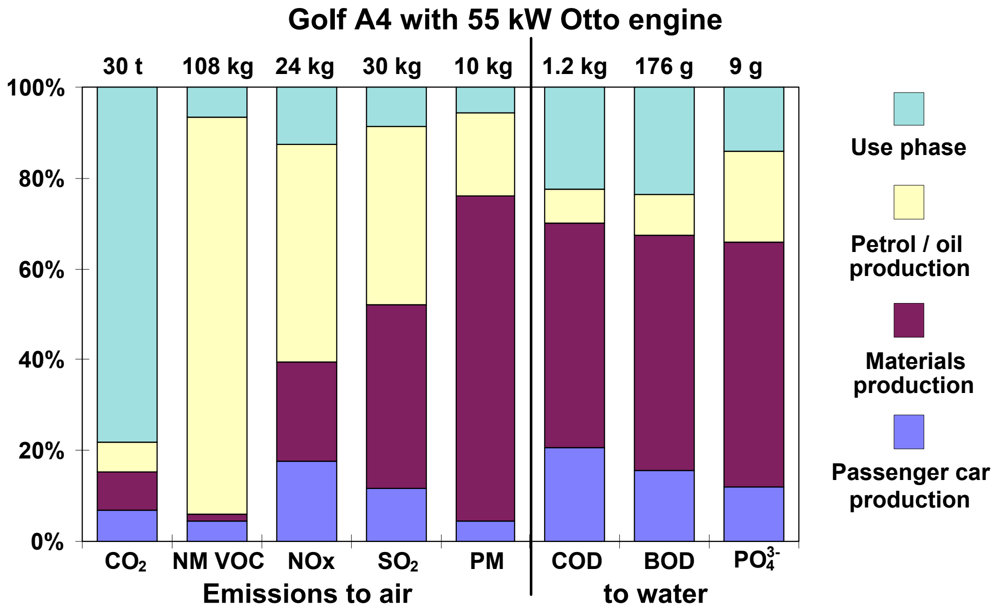
Primary energy		Total	Car production	Materials production	Fuel / oil production	Use and disposal
[r] Brown coal	GJ	4.50/4.66	1.93/1.92	2.19/2.34	0.02/0.02	0.35/0.39
[r] Hard coal	GJ	30.2/31.6	7.83/7.28	18.9/21.0	2.16/1.90	1.33/1.47
[r] Natural gas	GJ	43.3/43.6	14.5/14.8	14.4/15.0	9.26/8.12	5.11/5.66
[r] Crude oil	GJ	353/313	4.29/4.31	10.5/10.9	21.1/22.1	317/276
[r] Uranium (U) nat.	GJ	11.4/11.3	7.64/7.55	1.15/1.22	1.47/1.29	1.19/1.29
[r] Hydro power	GJ	2.54/2.56	1.36/1.35	0.87/0.88	0.05/0.05	0.25/0.28
Total	**GJ**	**445/407**	**37.6/37.2**	**48.0/51.2**	**34.1/33.4**	**325/285**
	MWh	124/113	10.4/10.3	13.3/14.2	9.47/9.28	90.4/79.2
	%	100.0	8.4/9.2	10.8/12.6	7.7/8.2	73.1/70.0
Chemical energy in the materials						
Synthetics	GJ			10.0/10.9		
Steel	GJ			4.68/5.33		
Light metals	GJ			1.61/1.55		
Others	GJ			0.75/0.77		
Total	**GJ**			**17.0/18.6**		

Figure 14: Energy pie graph from the Golf. The primary energy is calculated from the net calorific value of the resources. The Materials production column contains the mining and production of materials. The Car production column does not contain initial fuelling and initial oil filling. Both are included in the Use column. The chemical energy of the materials which is released during complete oxidation, i.e. returning to the original state of the resource, makes up 35% of the energy needed to produce the materials.

Material production requires the use of ore resources. Table 7 lists a selection.

	Golf A4, 55 kW Otto	Golf A4, 66 kW Diesel
Bauxite ($Al_2O_3.H_2O$) (21.1% Al)	25	21
Chrome ore	5.9	5.5
Dolomite ($CaMg(CO_3)_2$)	6.2	6.3
Iron ore (65% Fe)	1476	1622
Spar (Aluminium silicates)	6.0	6.0
Limestone ($CaCO_3$)	666	730
Copper ore	78	84
Platinum group ore	1977	1497
Sand	12	12
Rock salt (NaCl)	107	101
Titanium ore (0.6% Ti)	54	73
Zinc-lead ore (4.2% Zn, 5% Pb)	743	846

Table 7: Resources [kg] to produce the materials.



Emissions [kg/car]	Total	Car production	Materials production	Petrol / oil production	Use and disposal
[a] Carbon dioxide (CO_2)	29732	1890	2512	1991	23339
[a] NM VOC	107.6	4.8	1.6	94.3	7.0
[a] Nitrogen oxides (NO_x)	23.7	4.2	5.2	11.5	3.0
[a] Sulphur oxide (SO_2)	29.9	3.3	12.1	11.9	2.6
[a] Dust and PM	10.09	0.46	7.19	1.85	0.59
[w] Chemical oxygen demand (COD)	1.178	0.193	0.605	0.093	0.288
[w] Biochemical oxygen demand (BOD)	0.176	0.026	0.092	0.016	0.042
[w] Phosphates (PO_4^{3-})	0.009	0.001	0.006	0.002	0.001

Figure 15: Selected emissions for a driving distance of 150,000 km over 10 years and an average fuel consumption of 6.55 l/100 km. The particulate matter emission during the production phase is composed of dust, in the use phase it is particulate matter and dust. Engine exhaust is the source of 95% of the pollutants into the air from the use phase, excluding SO_2 and PM.

Figure 15 lists selected types of emission. Most of the emissions generated in connection with the production of materials and fuel are generated outside of Europe.

CO_2 emission is primarily due to material mining and, in the use phase, to the burning of fuel.

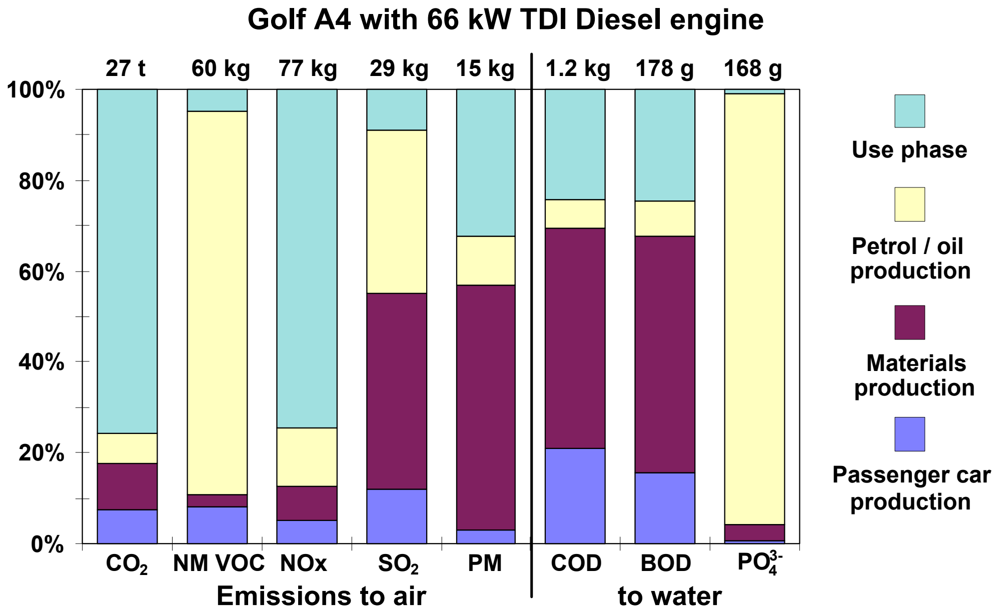
The majority of hydrocarbons (only the non-methane proportion NM VOC has been illustrated here) are generated by crude oil sources and by losses through petrol refilling.

The Golf's low NOx emission (13 mg/km) reflects the advancements made in the development of the 3-way catalytic converter. Please note the amount of ore moved, table 7.

SO_2 emissions come mainly from the production of fuel and materials. Half of the SO_2 in the use phase is produced by engine exhaust (the sulphur content in fuel was set at 100 ppm), the other half originates from the production of spare parts, including batteries, tyres and electricity.

The PM column combines the various dusts from the production phase and the particulate matter in the engine exhaust during the use phase. Tyre wear is shown separately (Table 10).

The BOD and COD emissions in the use phase are generated by car washings and the production of spare parts. Viewed in relation to the associated quantity of waste water (8 m³), these emissions are minimal.



Emissions [kg/car]	Total	Car production	Materials production	Petrol / oil production	Use and disposal
[a] Carbon dioxide (CO_2)	26602	1889	2688	1748	20277
[a] NM VOC	60.2	4.9	1.6	50.8	2.9
[a] Nitrogen oxides (NO_x)	77.5	3.8	5.6	10.1	57.7
[a] Sulphur oxide (SO_2)	28.5	3.2	12.3	10.4	2.6
[a] Dust and PM	14.61	0.46	7.77	1.62	4.76
[w] Chemical oxygen demand (COD)	1.176	0.196	0.593	0.082	0.306
[w] Biochemical oxygen demand (BOD)	0.178	0.026	0.093	0.014	0.044
[w] Phosphates (PO_4^{3-})	0.168	0.001	0.006	0.161	0.002

Figure 15a: Selected emissions for a driving distance of 150,000 km over 10 years and an average fuel consumption of 4.95 l/100 km. The particulate matter emission during the production phase is composed of dust, in the use phase it is particulate matter and dust. Engine exhaust is the source of 95% of the pollutants into the air from the use phase, excluding SO_2 and PM.

5.2 Mechanical Processing of the Base Engine at the Salzgitter Plant

The base engine is manufactured at the Salzgitter plant. Its weight corresponds approximately to half of the finished engine. Table 8 lists some of the inventory results. Many of the parts and blanks are not contained in this table, including exhaust valves, pistons, crankcase blanks, cylinder head, etc. To be able to view these figures from the right perspective, it is important to know that a total of 7500 engines are built every day (not for the Golf alone). Such a large quantity requires, in turn, large numbers of tools, shavings, emulsions, etc. (e.g. 7500 x 9.87 kg = 75 tn of used emulsion every day), making their processing worthwhile. The same applies to shavings.

Part	**Mass** kg	**Electricity** kWh	**Tools** g	**Shavings** g	**Scrap** g	**Emulsion** g
Crankcase	29.730	35.03	1.50	4768	247.00	593
Crankshaft	8.271	39.45	38.29	1368	54.46	1113
Flywheel	6.347	3.42	1.34	1177	15.00	934
Ring gear	0.505	2.05	13.35	246	3.22	670
Connecting rod, 4 pc.	1.490	17.88	5.73	779	17.63	904
Cylinder head	8.007	18.55	0.45	1989	0.94	887
Camshaft	2.187	14.40	13.89	419	43.22	709
Intake valve, 4 pc.	0.237	24.49	396.94	54	9.99	1374
Hydraulic valve lifter, 8 pc	0.305	3.43	3.59	17	6.99	657
Shavings washing		3.26				2030
Base engine assembly		12.89				
Emulsion recovery		0.47				
Total	**57.079**	**175.32**	**475.08**	**10817**	**398.45**	**9871**

Table 8: Mechanical processing of the base engine in Salzgitter. The tools consist of steel (20 g) and sanding disks (455 g). The shavings are disposed of, once separated into grey-cast iron, steel and aluminium. The remaining shavings and oil are removed from the used emulsion. 60% of the remaining water is sent into the sewage treatment system and 40% to the wash emulsion.

Having accumulated this data, we attempted to establish a ratio for processing expenditure against part weight. Unfortunately, we were unsuccessful. The extremely rough values are as follows: 3 kWh electricity and 0.2 kg shavings + scrap per kg of finished part.

Large grinding discs (120 kg) are used to give intake valves a finishing grind. After only comparatively little use, the grinding discs are forwarded for corundum recycling (crystalline Al_2O_3). This recycling has not been taken into account in the inventory - hence the conspicuously high tool consumption (400 g) for intake valves.

The 20 g of tool steel per engine adds up to 7500 x 20 g = 150 kg per workday. These tools are sometimes re-sharpened and put back to use, but the inventory does not take this into account.

5.3 Gearbox Manufacturing at the Kassel Plant

Since the first gearbox inventory was compiled in 1993, the aluminium smelting and refining plant in Kassel has been transformed to process aluminium scrap only (100%). The large cast components, gearbox housing, cylinder heads and engine blocks are cast using the AlSi9Cu3 alloy. The basic material consists of recycled façade parts, pipes, aluminium sheets of all kind and used cast parts. This aluminium scrap is first cut down to a size of 0.5 m and then shredded to fist-size. Iron and steel remnants such as bolts and reinforcements are magnetically separated.

Scrap aluminium is smelted in gas-heated rotary kilns. Silicon and copper are additionally alloyed as needed. Forklifts then transport small containers full of the liquid alloy to the die-casting machine, where it is directly processed. During the course of its passage from the scrap heap to becoming a finished gearbox housing, therefore, the scrap aluminium is smelted once only.

If there is not sufficient aluminium scrap, liquid aluminium is delivered from a smelting and refining works in Berlin using special tank lorries. On the journey from Berlin to Kassel, the liquid aluminium cools down by 40 – 60°C. These supplies of liquid aluminium are likewise processed from scrap aluminium.

The production of liquid aluminium from scrap products is energetically favourable. Because of the low smelting temperature, it requires less energy than does the smelting of scrap iron.

New inventory of the Golf A4

Parts	**Materials kg**	**Electricity kWh**	**Heat kWh**	**Tools g**	**Shavings kg**	**Scrap kg**
Casing (100% sec. AlSi9Cu3)	16.47	46.5	35.0	0.2	1.12	5.12
Input shaft with gears	7.31	20.7	15.2	4.1	3.47	0.07
Output shaft with gears	7.62	18.0	14.9	2.9	2.87	0.11
Differential	8.50	18.5	17.4	3.0	1.91	0.60
Shift parts	1.37	1.9	2.2	0.5	0.37	0.01
Others	8.25	12.5	4.0			1.04
Total	**49.51**	**118.1**	**88.6**	**10.6**	**9.73**	**6.95**

Old inventory of the Golf A3

Parts	**Materials kg**	**Electricity kWh**	**Heat kWh**	**Tools g**	**Shavings kg**	**Scrap kg**
Casing (50% prim. Al)	11.65	25.4	22.7			
Steel parts	28.56	131	45.3			13.3
Others	0.8					
Total	**41.01**	**156.4**	**68.1**			**13.3**

Table 9: Gear box production at the VW plant Kassel. The new inventory shows the materials and energy requirement for the main assemblies. The old inventory was less detailed and the energy demand was incomplete because the energy to produce 5.8 kg of primary aluminium was not taken into account (175 MJ primary energy / kg Al).

Shafts and wheels are forged from bar stocks. This material is heated using electric induction, a process for which 0.7 kWh of electricity is required per blank kg. Mechanical processing (blasting, turning, milling, rolling, …) requires a further 1.5 kWh. The electricity used for lighting denotes approx. 5% of the overall demand for electricity.

Workshop heating is a major item. Around 1/3 of the overall demand for heating is room heating. A large share of room heating demand had already been established for production at the Wolfsburg plant (see Table 3).

6 Comments on the Results

The primary finding of this life cycle inventory is that the majority of energy is consumed during the use phase. Approximately 9% of total energy is needed to manufacture the vehicle, 12% to mine the materials and a further 8% to provide the required fuel. The remainder, 71%, is attributable to the use phase, of which the majority, in turn, can be attributed to the calorific value of the fuel burned during the 150000 km driving distance and to the spare parts (tyres). The fact that the energy required to manufacture the vehicle increases from one model to the next while the overall energy demand is reduced, was a new discovery, as was the fact that more energy is required to mine the materials than to produce the vehicle.

During the use phase, only a few atmospheric emissions are predominant, including those coupled to energy consumption, i.e. CO_2, CO and NOx emissions. It was surprising to find that many other emissions dominate the production phase. For example, the majority of hydrocarbon and sulphuric oxide emissions are generated during the production and distribution of fuel. And the greatest amount of metal and chlorine is emitted during the mining of raw materials.

The quantities of metal in the ore are smaller than the quantities built into the vehicle. This is a consequence of metal recycling. Car makers use mainly steel from fresh ore. Recycled iron is used in other steel-utilising industries. The alloy used in automobile production contains a large proportion of secondary aluminium - up to 90%.

Water consumption of 95 m^3 per car can be broken down into that needed for electric power generation (46 m^3), fuel production (23 m^3), car washing (8 m^3), material production (10 m^3) and other factors (9 m^3). The figure set for the water needed to secure the energy carriers (electricity and fuel) has been somewhat randomly fixed, as were those for the mining of other raw materials. This is because circulation water is often used which may, for example, be taken from a river and later returned to it. Waste water from the car wash would, in itself, have a relatively low level of contamination. Since, however, non-related air and ground impurities are adsorbed by a vehicle and issued into the waste water, there is a shift to the problem.

Throughout the course of its life cycle, the 66-kW TDI-engine Golf emits 3 tn less CO_2 and 40 kg less NM VOC than the same vehicle with a 55 kWh petrol engine. Conversely, it generates 50 kg more NOx and 5 kg more dust/particulate matter.

One of the weaknesses of the petrol-fuelled vehicle is the NM VOC emission generated, for the most part, through fuel distribution, since fuel vapour recovery during the filling procedure does not work properly in practice. In the diesel vehicle, it is the NOx emission that is the most significant weak point. This emission is generated during vehicle operation. If we make a proportionate comparison of the regulated emissions (NM VOC, NOx, SO_2 and particulate matter) and CO_2 emission, we can establish that exhaust emission control has reached a high degree of advancement. Regulated emissions total no more than 0.6% of the CO_2 mass.

The automobile is the consumer article with the highest rate of recycling - even higher than for paper. The reason for this is that a car cannot be simply thrown into the rubbish container, apart from which metal recycling has reached a very high standard. As far as used synthetics are concerned, this material is being increasingly subjected to thermal recycling.

Some of the information in the life cycle inventory is outdated. This is due to the vast quantity of data and the fact that it takes several years to acquire it, during which time a number of processes will have been modernised, with no time available to update the inventory data.

A good deal of uncertain data has thus been included, even though the author is well aware of the existence of erroneous values. This should provide incentive to make better data available.

The evaluation of the figures is not easy. There is a lack of references against which they can be compared. Are the 8 m^3 of water used during the 10-year use phase for car washing excessive? Or are they, on the contrary, below average? We can compare water consumption with that of an average household: approx. 50 m^3 per person per year.

Emissions into water, among them chemical (COD) and biochemical (BOD) oxygen demands, as well as the total amount of nitrogen emission (nitrite, nitrate, ammonium, ammonia) are so low because the water concerned is waste water which has already undergone treatment. To allow us to put things into perspective, we herewith refer to the BOD standard value for untreated communal waste water, which is 60 g per inhabitant per day.

Having conducted the inventory and analysed the figures, it becomes clear that the range of variation in the data is far larger than the typical margin of error for technical measurements. The causes are of a systematic nature, founded on imprecisely defined system boundaries for the inventory, on the simultaneous existence of dated and modern production systems, on individual driving styles which, from a statistical standpoint, are difficult to ascertain with any precision, etc. Irrespective of these factors, however, the results of the life cycle inventories conducted to date [1, 3, 4 and the one at hand] are unexpectedly stable.

New, additional modules evolve with every new life cycle inventory; and new links are created between existing databases within the plants. A common database (IMDS) is currently being set up within the sector that embraces the automotive industry and its suppliers.

This LCI has shown that, while we need to make use of the special expertise of the companies involved, it is not necessary to disclose such it. All such concerns have proven to be unfounded.

Primary-Resources, ores	Production mat.+car	Production fuel+oil	Use car	Energy carriers	Production mat.+car	Production fuel+oil	Use car
Bauxite 21% Al [kg]	25			Primary energy [GJ]	86	34	325
Lead 5% [kg]	740						
Chromium 20% [kg]	6						
Iron 66% [kg]	1476			Brown coal [GJ]	4		
Copper 0.3% [kg]	78			Hard coal [GJ]	27	2	1
Nickel 70% [kg]	2			Natural gas[GJ]	29	9	5
Platinum [kg]	2000			Crude oil [GJ]	15	21	317
Zinc 4% [kg]	(740+5)			Nuclear power [GJ]	9	1	1
Limestone [kg]	666			Hydro power [GJ]	2		
Rock salt [kg]	100		7				
Water [m³]	57	23	15				
			Emissions to air				
CO_2 [tn]	4	2	23	H_2SO_4 [g]	1.2		
CO [kg]	23	1	16	HCl [g]	154	65	4
NM VOC [kg]	6	94	7	HF [g]	39	9	2
CH_4 [kg]	17	0.3	3	H_2S [g]	4	0.1	0.3
NOx [kg]	9	12	3	C_6H_6 [g]	4	1	470
N_2O [kg]	0.3		6	PAH [g]	0.6		2
NH_3 [kg]			0.9	Cu [g]	3		0.9
SO_2 [kg]	15	12	3	Mn [g]	2		
Dust and PM [kg]	8	2	0.6	Heavy metals [g]	15		2
			Emissions to water				
AOX [g]	4	0.1	0.6	Na^+ [g]	26	5	260
COD [g]	800	93	290	Fe [g]	6	80	1
BOD [g]	120	16	42	Cu [g]	0.1	0.8	2
TOC [g]	440	50	110	Zn [g]	2		2
Total N [g]	18	0.1	5	Heavy metals [g]	22	1	9
Phenols [g]	1	1	0.6	HC [g]	110	700	250
Cl^- [g]	1200	29	63	Oil [g]	9		
PO_4^{3-} [g]	6	2	1.4	PAH [g]	0.6	8	
SO_4^{2-} [g]	850	720	22				
			Emissions to land				
Ash [kg]	21	10	3	Cr slag[kg]	105		
Waste liquid [kg]		0.5		Cu slag [kg]	25		1
Waste solid [kg]	150	1	30	Ni slag [kg]	12		
Tyre wear [kg]			12	Paint sediment [kg]	3		
Domestic waste [kg]	85		85	Ore residue [tn]	8		
Toxic waste [kg]	5		11	Excava. waste [tn]	3		

Table 10: Selected resources, without secondary materials, for the production and operation of a Golf with 55 kW Otto engine, and some emissions. Empty fields are negligible or unknown. During the End of Life phase 60 kg of solid waste are disposed. Waste for recovery, e.g. stamp residues, are not listed here. Cu, Fe, Mn and Zn emissions are also included in the heavy metal emissions. Figures on wastes are incomplete due to the coarse classification.

The figures are quite uncertain, e.g. the sulphur emission will be halved in the use phase if the sulphur content in the fuel would be reduced from 100 to 0 ppm. The tolerance for energy values is estimated to ±15%, regulated emissions (CO_2, NM VOC, NOx, SO_2, PM) to ±30%. Unregulated emission can differ up to a factor of 10.

Abbreviations

ABS	Acrylonitrile-butadiene-styrene copolymer plastic
AOX	Adsorbable organically bonded halogens
BOD	Biochemical oxygen demand for treatment of waste water
CML	Centrum voor Milieukunde, Netherlands
CN	Cetan number
COD	Chemical oxygen demand for treatment of waste water
EPDM	Ethylene-propylene-diene rubber
GJ	Gigajoules = 10^9 joules, unit of measurement for primary energy
IMDS	International Material Data System
IPCC	Intergovernmental Panel on Climate Change, Geneva, Switzerland
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MDI	Methylene diisocyanate plastic
MWh	1 MWh = 3.6 GJ
NEDC	New European Driving Cycle
NM VOC	Non-methane volatile organic compounds
PA 6	Polyamide 6 $NH(CH_2)_6NH$ synthetic
PA 6.6	Polyamide 6.6 $[NH(CH_2)_4NH][CO(CH_2)_6CO]$ synthetic
PAH	Polyaromatic hydrocarbons
PE HD	High-density polyethylene CH_2 plastic
PM	Particulate matter in the exhaust gas
PMMA	Polymethyl methacrylate $CH_2CCH_3COOCH_3$ plastic
POM	Polyoxymethylene (CH_2O)
POX	Purgeable organically bonded halogens
PP	Polypropylene $(CH_2)(CHCH_3)$ plastic
PPE/PPO	Polyphenylene ether/polyphenylene oxide C_6H_5O plastic
PS	Polystyrene $(CH_2)(CHC_6H_5)$ plastic
PUR	Polyurethane $OCONH(CH_2)_yNHCOO(CH_2)_x$ plastic
PVC	Polyvinyl chloride $(CH_2)(CHCl)$ plastic
R&D	Research and Development
RME	Rapeseed methyl ether, biodiesel
UP	Unsaturated polyester

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8 Enclosures

Enclosure 1: Technical Description of Golf A4, 4-Door, 1.4 l 55 kW Petrol Engine

Engine	**Petrol Eng.**	
Type		4-cylinder in line, front, transverse
Displacement	cm^3	1390
Bore and stroke	mm	76.5 x 75.6
Compression ratio		10.5 : 1
Maximum performance	kW / hp / min^{-1}	55 / 75 / 5000
Maximum torque	Nm / min^{-1}	128 / 3300
Fuel system		Electronic direct multipoint injection
Ignition		Electronic-map ignition, selective knock control
Fuel		Premium unleaded / regular, min. 95 RON
Exhaust control		Three-way catalyst, Lambda detector
Alternator	A	70
Battery	Ah / A	44 / 220
Gearbox		5-speed manual gearbox
Performance		
Maximum speed	km/h	171
Acceleration 0-80 / 100 km/h	s	9.2 / 13.9
Consumption		Based on a reference mass of 1130 kg
Urban cycle / non-urban	l/100 km	8.4 / 5.3
NEDC	l/100 km	6.55
CO_2 emission	g/km	154
Chassis		
Front axle suspension		Coil spring with telescopic shock absorber integrated in suspension strut. Wishbone
Rear axle suspension		Gas shock absorber with separate spring. Twist-beam rear axle, track-correcting bearings
Steering		Hydraulic rack-and-pinion steering. Safety steering column
Turning circle	m	10.9
Brakes		Hydraulic, dual-circuit diagonal servo brakes and ABS
Front / rear brakes		Ventilated / non-ventilated disc brakes
Rims	inches	6J x 14
Tyres		175/80 R14
Body Structure		
Type		4-door, 5 seats
Length / width / height	mm	4149 / 1735 / 1439
Wheel base	mm	2511
Track front / rear	mm	1513 / 1494
Luggage compartment capacity	l	330 / 1184 (min./ max.)
Maximum fuel tank capacity	l	55
Corrosion Control		Fully galvanised, plastic wheel housing liners
Weight		
Curb weight (excluding driver)	kg	1043
Total permissible weight	kg	1640

Technical Description of Golf A4, 4-Door, 1.9 l 66 kW TDI Engine

Engine	**TDI Diesel**	
Type		4-cylinder in line, front, transverse
Displacement	cm³	1896
Bore and stroke	mm	79.5 x 95.5
Compression ratio		19.5 : 1
Maximum performance	kW / hp / min^{-1}	66 / 90 / 3750
Maximum torque	Nm / min^{-1}	210 / 1900
Fuel system		Electronic cylinder multipoint injection, turbocharger, inter cooler / oil cooler
Fuel		Diesel CN ≥ 49, RME
Exhaust control		Exhaust gas re-circulation, oxidising converter
Alternator	A	70
Battery	Ah / A	61 / 330
Gearbox		5-speed manual gearbox
Performance		
Maximum speed	km/h	180
Acceleration 0-80/ 100 km/h	s	8.4/ 12.4
Consumption		Based on a reference mass of 1250 kg
Urban cycle / non-urban	l/100 km	6.5 / 4.1
NEDC	l/100 km	4.95
CO_2 emission	g/km	132
Chassis		
Front axle suspension		Coil spring with telescopic shock absorber integrated in suspension strut. Wishbone
Rear axle suspension		Gas shock absorber with separate spring. Twist-beam rear axle, track-correcting bearings
Steering		Hydraulic rack-and-pinion steering. Safety steering column
Turning circle	m	10.9
Brakes		Hydraulic, dual-circuit diagonal servo brakes and ABS
Front / rear brakes		Ventilated / non-ventilated disc brakes
Rims	inches	6J x 15
Tyres		195/65 R15
Body Structure		
Type		4-door, 5 seats
Length / width / height	mm	4149 / 1735 / 1439
Wheel base	mm	2511
Track front / rear	mm	1513 / 1494
Luggage compartment capacity	l	330 / 1184 (min./ max.)
Maximum fuel tank capacity	l	55
Corrosion Control		Fully galvanised, plastic wheel housing liners
Weight		
Curb weight (excluding driver)	kg	1164
Total permissible weight	kg	1740

Enclosure 2: Impact Potentials

Acidification Potential

The reference substance is sulphur dioxide (SO_2). The mass to be determined is the acid-producer mass created by dissolution in water. For SO_2 it is SO_2^{--}, i.e. (32 + 2x16)/2 = 32 kg of acid producers are created per kilomole and negative valence. Other substances create other acid producers, the masses of which are chemically defined, e.g. NO_2 creates NO_2^- with (14 + 2x16)/1 = 46 kg per valence.

The acidification potential equals the mass of acid producers of a given substance in relation to the SO_2 acid producer. For NO_2, this was 32/46 = 0.696, i.e. 1 kg NO_2 = 0.696 kg $SO_{2\ \mathrm{equiv.}}$

Carbon dioxide (CO_2) is not taken into account, even though it contributes considerably to the pH value of the water.

Greenhouse Effect

As an introduction to the term ”greenhouse effect”, we will describe 2 simple radiation models. The first thing we need is the radiation of a black body (cavity radiation), which follows Planck’s law of radiation:

$$S(\lambda, T) = \frac{2\pi c^2 h}{\lambda^5 \left(e^{\frac{ch}{\lambda kT}} - 1 \right)}$$

$$\int_0^\infty S(\lambda, T) \mathrm{d}\lambda = \sigma T^4$$

$$\lambda_m T = \frac{ch}{4.9651142k} = 2.8978210^{-3} \mathrm{mK}$$

$$\sigma = \frac{2\pi^5 k^4}{15 h^3 c^2} = 5.669210^{-8} \frac{\mathrm{W}}{\mathrm{m^2 K^4}}$$

c	2.99793 10^8 m/s	speed of light
h	6.62517 10^{-34} Ws²	Planck constant
k	1.38044 10^{-23} Ws/K	Boltzmann constant
λ	wavelength of radiation	
λ_m	wavelength at maximum intensity	
σ	Stefan Boltzmann constant	
$S(\lambda, T)$	radiant power [W/m³] in relation to the cross section of void opening and the recorded wavelength interval	

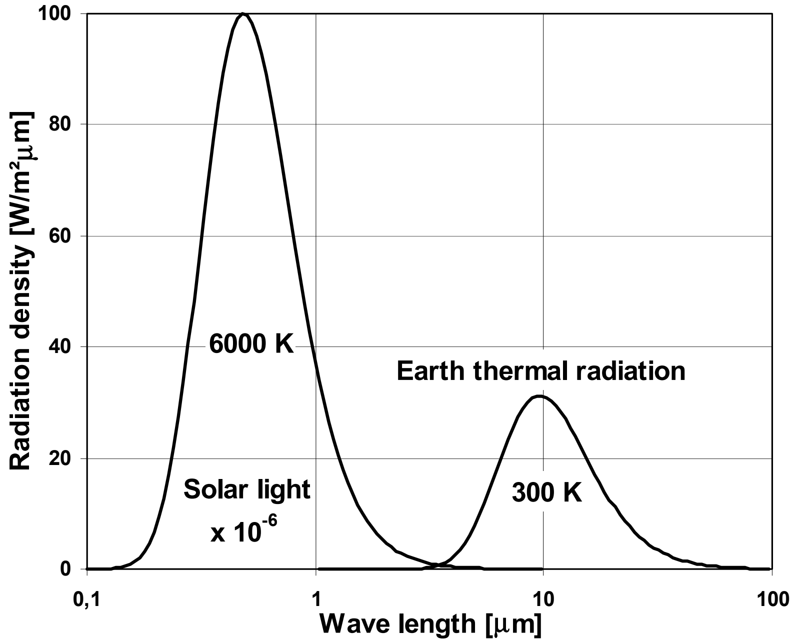


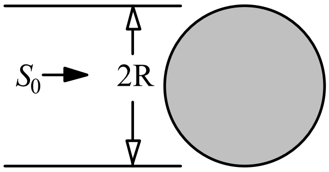
Figure A1: Cavity radiation at 6000 and 300 K, calculated with Planck's formula $S(\lambda, T)$, typical for the solar light and the earth thermal radiation. The cavity radiation at 6000 K is down scaled by a factor of 10^6 to fit it into the figure.

Practice exercise: A globe circles around the sun in a similar orbit to the earth. The globe has no atmosphere and rotates quickly around its own axis in order to warm up uniformly. How warm will the globe become?

Data:

S_0	1353 ± 27 W/m²	Solar constant with variation through elliptical earth orbit
r	0.3	Reflection coefficient for the incident radiation
e	0.95	Emission coefficient for the thermal radiation

Solution: The globe will receive radiation from the sun on its cross section πR^2 only, but its total surface $4\pi R^2$ will radiate heat. The balance between irradiation and radiation is

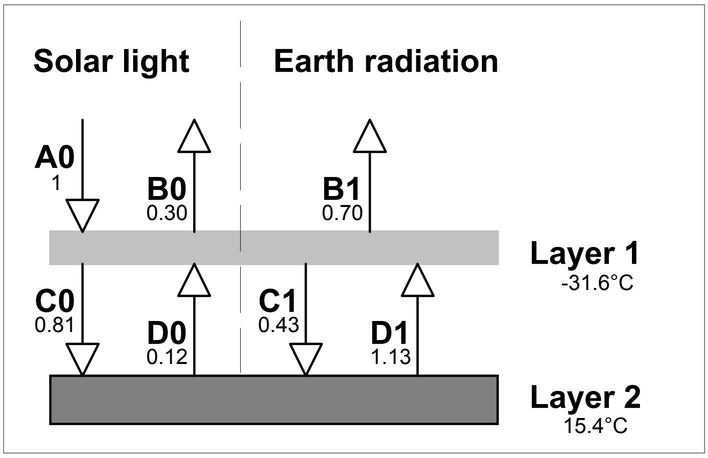


$$S_0 \cdot (1-r) \cdot \pi R^2 = 4\pi R^2 \cdot e \cdot \sigma \cdot T^4$$

$$T^4 = \frac{S_0}{4\sigma} \cdot \frac{1-r}{e}$$

and a the temperature = 257.5 K = -15.6°C results.

The greenhouse effect can be simulated by enveloping the globe with a layer of glass, resulting in the following model:



Data

A0 = S_0/4 = 338.25 W/m²

		Lambda 0	Lambda 1
Layer 1	r	0.20	0.01
	a	0.01	0.74
Layer 2	r	0.15	0.05
	a	0.85	0.95

r + a + t = 1 for each wavelength

The following equations apply to the energy flows. It is relatively simple to compute sequential solutions using Excel or a similar application.

Equation	
$A0 = B0 + B1$	Radiation balance in the area above layer 1
$C0 + C1 = D0 + D1$	Radiation balance in the area between the layers
$B0 = r_{01} \cdot A0 + t_{01} \cdot D0$	Reflection and transmission of layer 1 of wavelength 0
$C0 = t_{01} \cdot A0 + r_{01} \cdot D0$	Transmission and reflection of layer 1 of wavelength 0
$D0 = r_{02} \cdot C0$	Reflection of layer 2 of wavelength 0
$S1 = a_{01} \cdot A0 + a_{01} \cdot D0 + a_{11} \cdot D1$	Temperature radiation of layer 1 at wavelength 1
$B1 = 0.5 \cdot S1 + t_{11} \cdot D1$	Composition of B1
$C1 = 0.5 \cdot S1 + r_{11} \cdot D1$	Composition of C1
$D1 = S2 + r_{12} \cdot C1$	Composition of D1

Temperatures

$T1 = [0.5 \cdot S1 \cdot A0/(a_{11} \cdot \sigma)]^{1/4}$

$T2 = [S2 \cdot A0/(a_{12} \cdot \sigma)]^{1/4}$

The essential result is the flow of heat, D1, which is greater than the day-average incidental sun radiation, A0. The glass (layer 1) absorbs thermal radiation and returns half of the heat to the globe (layer 2) and the other half into space, so that cosy warmth is created between both layers.

The greenhouse effect on earth is more complicated. 60 to 80% of the sun's radiation reaches the earth's surface, directly or indirectly. There, approx. 75% of it is absorbed; the oceans are fairly black. The absorbed radiation, be it that in the atmosphere or on the ground, is returned as diffuse temperature radiation of –60 to +30°C. The lower atmospheric layers are impenetrable, i.e. thermal radiation has a reach of several hundred metres. A temperature gradient develops which, in the troposphere, is determined by the polytropical expansion of humid air (up and down currents). In those regions where relative humidity sinks to below 10% at –50°C, tropopause is created, meaning the temperature gradient changes to positive.

Virtually the whole of the greenhouse effect is generated by atmospheric water vapour. It is assumed that the water vapour is in quick equilibrium with the earth's moist surface and that relative humidity remains constant when temperatures change. Based on this assumption, the tables used for greenhouse potential do not contain water (H_2O).

The atmospheric temperature shows a delayed reaction to changes in radiation by the sun. The time constant is short – around one month. We are familiar with this phenomenon in the fluctuation of day, night and seasonal temperatures. Additionally, there is a long-term effect caused by the mineralisation of CO_2 (i.e. $CaCO_3$ - of which the Dolomites are made - is created), by CO_2 exchange with deep layers in the oceans and by the adaptation of vegetation to the changed temperature and humidity.

Greenhouse-relevant gases become effective via their infrared absorption and their retention time in the atmosphere. The effect is the stronger the absorption and the longer the gas remains in the atmosphere. Short-lived gases, e.g. carbon monoxide (CO), create a minimal greenhouse effect, at least if they are not constantly refilled. The term short-lived, in this context, denotes a period of less than 10 years.

To define the greenhouse equivalent, it is necessary to also allot carbon dioxide a life period within the atmosphere. This is not a simple matter, because it refers to the lengthy time constant with which the concentration of CO_2 follows a step change in solar radiation intensity. We assume, more or less randomly (in accordance with the latest knowledge base), a CO_2 half-life period of 120 years. For other gases, infrared absorption has been measured and a half-life period defined. From this, we can calculate the greenhouse potentials.

Now for another example of how the greenhouse potentials and the values of this life cycle inventory are used to compute an overall greenhouse equivalent:

Greenhouse Gas	**Greenhouse potential 100 years**	**Amount in kg according to inventory**	**Greenhouse equivalent kg $CO_{2\ \text{equiv.}}$**
CO_2	1	29732	29732
N_2O	320	6.459	2067
R134a (CFH_2CF_3)	1300	1.5	1950
CH_4	24.5	20.47	502
SF_6	24900	$12.2\ 10^{-6}$	0.30
R14 (CF_4)	6300	$20.7\ 10^{-6}$	0.13
R116 (C_2F_6)	12500	$2.3\ 10^{-6}$	0.03
Total CO_2 equivalent			**34251**