# QUANTIFYING THE LIFE CYCLE WATER CONSUMPTION OF A PASSENGER VEHICLE

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# QUANTIFYING THE LIFE CYCLE WATER CONSUMPTION OF A PASSENGER VEHICLE

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# SUMMARY

Various studies have pointed out the growing need to assess the availability of water sources in regions around the world as future forecasts suggest that water demands will increase significantly for agricultural, industrial and human consumption while freshwater resources are being depleted. One such emerging issue is the effect of industrial operations on said resources, specifically from automobiles. With numerous localities experiencing stresses on water availability, key stakeholders - suppliers, automakers, and vehicle end-users - need to better realize the effect vehicle manufacturing, usage, and disposal have on water resources.

While efforts to improve the overall environmental performance of vehicles have mainly concentrated on improving technologies, there has also been considerable effort devoted to characterizing the life-cycle performance of the vehicle product system. However, much of this work has focused on energy consumption and carbon emissions while few studies have examined water. The difference between water use versus water consumption were highlighted and the life-cycle water consumption of a gasoline-powered midsize vehicle were analyzed from material extraction through production, use, and final disposition/end of life. This analysis examines each of the phases to determine a car's water footprint using data from the EcoInvent Life Cycle Analysis database as well as data collected from literature sources. Although water use is typically metered at the factory level, water consumption (i.e., water lost through evaporation and/or incorporation into a material, part, and/or product) is much harder to quantify. As shown in this thesis, the difference can be an order of magnitude or more because much of the water that goes into the different processes is either reused, recycled, or discharged back to its original source. The use phase of a vehicle has the biggest impact on the overall vehicle water consumption, followed by material production, whereas water consumption for the end of life processing seems to be relatively insignificant. It is also shown that the

impact of energy consumption as part of the total water footprint is very large when compared to the other processes given the dependence on water for energy production.

The assessment in this thesis represents a life-cycle inventory and serves as an initial benchmark as no previous study has been completed to determine the water consumption for the life of a vehicle, let alone for most other products. The impact of water consumption varies by region and locality, and a differentiation of impact would still be needed to determine whether the water consumption actually happens in water scarce regions or not.

# CHAPTER 1

# INTRODUCTION

## 1.1 Water Scarcity

Water is a prerequisite for life on earth. It is an essential natural resource for basic human needs such as food, drinking water and a healthy environment. Human beings are inextricably linked to freshwater for personal sustenance, basic hygiene, growing crops, producing energy, manufacturing goods and maintaining ecosystems (Yen, Zullo et al. 2011). However, having access to not just the right quantity but also the right quality of water has become critical issue requiring proper management of water resources to ensure a healthy future.

Water scarcity is among the main problems to be faced by many societies and the World in the 21st century. Water use has been growing at more than twice the rate of population increase in the last century, and, although there is no global water scarcity as such, an increasing number of regions are chronically short of water which creates a less than healthy living environment and hinders future economic development (UN-Water 2007). Water scarcity already affects every continent. Around 1.2 billion people, or almost one-fifth of the world's population, live in areas of physical scarcity, and 500 million people are approaching this situation. Another 1.6 billion people, or almost one quarter of the world's population, face economic water shortage and will continue to be in this position for years to come (UN-Water 2007) .

Water scarcity is both a natural and a human-made phenomenon. There is enough freshwater on the planet for seven billion people but it is distributed unevenly, as shown in Figure 1, and too much of it is wasted, polluted and unsustainably managed (UN-Water 2007). Poor management of resources allows for grave inefficiencies that worsen the problems. As population increases and development call for increased allocations of groundwater and surface water for the domestic, agricultural and industrial sectors, the pressure on water resources intensifies, leading to tensions, conflicts among users, and excessive pressure on the environment. The increasing stress on freshwater resources brought about by ever-rising demand and profligate use, as well as by growing pollution worldwide, is of serious concern that should be prioritized in the future to develop more sustainable strategies for water use (UN-Water 2007). The need for freshwater in some locations has already led to water allotments, shifts towards full-cost water pricing, more stringent water quality regulations, growing community opposition, and increased public scrutiny over water practices (Yen, Zullo et al. 2011).

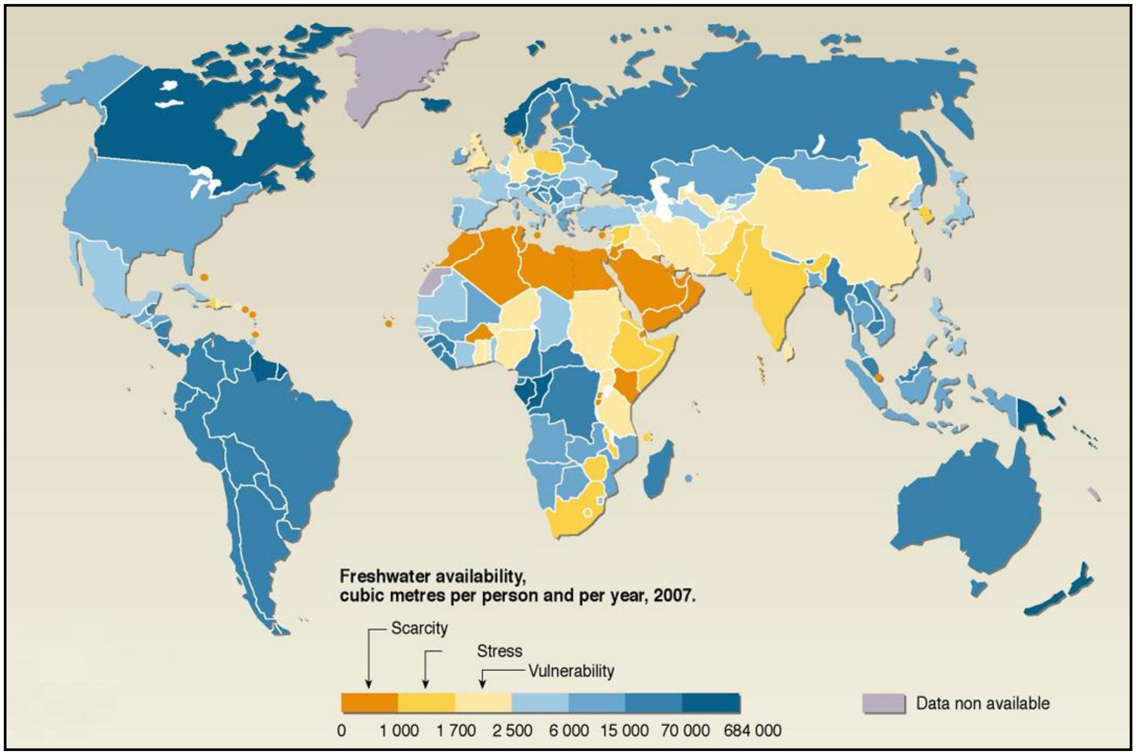

Figure 1: Freshwater Availability(UN-Water 2007)

Scarcity has various causes, most capable of being remedied or alleviated. A society facing water scarcity usually has options. However, scarcity often has its roots in water shortage, and it is in the arid and semi-arid regions affected by droughts and wide climate variability, combined with high population growth and economic development, that the problems of water scarcity are most acute (UN-Water 2007). In other words, water use is a much different issue from greenhouse gas emissions because water has a local impact versus the global impact of greenhouse gas emissions. In regions that have a surplus of water, variations in the level of water use may have little noticeable impact. However, in water scarce regions, the same water use could put extreme strain on the available water resources.

Models and assessments of the water use must be developed for better water management and to create more effective policies. These analyses can help to integrate water strategies into the national planning process and water concerns into all government policies and priorities, and the may additionally bring governments to consider the water resource implications of these actions (Yen, Zullo et al. 2011). Through legislative policies, goals can be set for water use, protection, and conservation by allocating financial resources to meet water needs. Ultimately, these tools can serve as social change instruments – encouraging a water-oriented society that manages disputes and ensures the sharing of water by determining water use limits and equitable and efficient allocations (Yen, Zullo et al. 2011).

## 1.2 The Dependence of Industry on Water

Water is an intricate and vital aspect of manufacturing. As humans need water to fulfill their basics needs, manufacturing operations need water to complete their basic functions. Without the right amount of clean water, most products simply could not be manufactured. Water in manufacturing is directly used for three main purposes: cooling, processing, and cleaning. This generalization extends across all operations regardless of the final product or the intermediate processes required. Water in manufacturing is also indirectly used for the production of energy. Energy is required to run the machinery and water is required to produce this energy thus water is indirectly required to run the machinery.

Cooling water in a manufacturing environment is used to help regulate temperatures. Most every manufacturing process involves the use of energy. Water is often the most acceptable medium to transfer heat away from the machinery, material, parts or assemblies. There are three main methods of accomplishing this transfer: single pass, recirculating cooling pond, and cooling tower. All have their benefits and drawbacks although recirculating water through a pond or cooling tower is typically a more environmentally friendly and economically sound decision. By reusing resources, less is wasted and the systems are more efficient.

Water in processing is used to ensure proper manufacturing conditions. Water’s wide range of properties allows it to be used in a variety of operations. For instance, it can be used for rinsing products, parts and vessels. Water can also be used as a lubricant, as a solvent or reactant in a chemical reaction, as a seal to block out contact with air, or in pollution control. Water in processing serves as a medium to ensure that manufacturing conditions are ideal and that they yield the desired effect on the final product.

Water in cleaning is used to attain better working conditions and to ensure that parts and facilities meet the expected hygienic requirements. To ensure the production of quality products, parts are often cleaned after each manufacturing process with water as the main agent. The facilities must also be maintained properly, sometimes to meet government regulations, but often, simply to have appropriate working conditions for personnel.

And finally, water is used in manufacturing, indirectly, to produce the energy. In the context of power generation, water serves a similar purpose to that of manufacturing cooling; it removes excess heat to allow for a normal continuing operation. Water can be consumed in this context through evaporation in a normal power plant, or even as stagnant water exposed to more heat from the sun in hydroelectric dams. Water is not just used to produce the electricity but also to produce other form of energy.

Water's ever-growing importance in the industrial manufacturing arena has been demonstrated by an increasing concern regarding the sufficiency of both its quantity and quality for use in industrial applications for cooling, processing, and cleaning. Diminishing quality water supplies, increasing water purchase costs, and strict environmental effluent standards are forcing industries to target increased water-efficiency and to reuse in order to decrease their water footprint (Ellis, Dillich et al. 2000). These concerns are even greater in scarce and stresses areas where water can be seen as a valuable commodity not to be wasted. In order to maximize the water consumption reduction strategies, proper assessments of where and how much water is consumed in manufacturing must be developed to better identify areas of concern. These assessments can lead to the introduction and implementation of more efficient technologies.

### 1.3 Motivation: Water in the Life of a Passenger Vehicle

Automobiles are an essential part of our economy, satisfying a broad range of consumer mobility needs. Though they provide tremendous value to their owners, these vehicles are, nevertheless, conspicuous consumers of resources, which have led to a great deal of effort to improve their efficiency and overall environmental performance. While much of this work has focused on improved vehicle technology, there has also been considerable effort devoted to characterizing the life-cycle performance of the vehicle product system. (Sullivan, Burnham et al. 2010). The objective of life-cycle inventory is to develop an environmental "picture" of product systems, one where life-cycle burdens, such as energy, carbon dioxide emissions, water consumption, and raw materials, are quantified and evaluated over all stages of a product's life cycle. Hence, tradeoffs between life-cycle stages can be accounted for, resulting in more holistic assessments of product systems and often illuminating improvement opportunities (Sullivan, Burnham et al. 2010). For example, vehicles made lighter by substituting materials like aluminum and composites for steel do indeed have higher fuel economy, but at the same time a part of that benefit is offset by the generally higher production energies of alternative materials. While electric-drive vehicles use less energy during operation than their spark-ignited counterparts, the energy required to make constituent materials and assemble them into batteries may offset a major portion of the benefit. These examples and many others show the merit of life cycle inventory, and illustrate it as a method that focuses not just on the product (or process) and its use but also the infrastructure needed to make, maintain, and dispose of it. Indeed, for automobiles, considerable resources (materials, energy, and water) are consumed and emissions (environmental burdens) generated during their production (Sullivan, Burnham et al. 2010). Whole vehicle-systems life cycle inventory estimate the holistic impact of the vehicle product system on the environment. To do this meaningfully, the ideal total vehicle cycle study should have boundaries that include all process and material flows associated with the vehicle life cycle stages.

Understanding water as part of the life of a vehicle is not only important from an academic, environmental, and social point of view, it is also a pertinent issue to businesses, whose activities often are heavily reliant on access to the right quantity of quality water for a continued success. The issue of water scarcity and how it relates to water for businesses is about understanding water risk and resultant business risk (operational, regulatory, and reputational). To better realize and quantify areas needing further investigation or reorganization because of their high impact, a proper model of the entire life cycle needs to be created. This model can help to not just quantify how much water is being consumed, but more importantly, to define how it is being consumed which could lead to the restructuring of their supply chain or a shift in the focus of resources.

## 1.4 Water Consumption vs. Water use

An important first step to quantify the environmental resource depletion for the life of a vehicle is to properly define how water plays a role. In other words, a clearly stated definition of the focus should be given. In this thesis, water consumption and water use is distinguished as such:

- Water consumption is defined as freshwater withdrawals which are evaporated, incorporated in products and waste. Basically, the water molecule is not available in liquid form for (re)use after it is consumed, at least not immediately
- Water Use is defined as all water that goes into a system. Most of this typically leaves the system as waste water. The difference between the amount of liquid input water and liquid waste water is the water consumption.

The definitions for this thesis are consistent with those of ISO standard 14046, currently being developed. In this standard, water consumption is defined as water withdrawal where release back to the source of origin does not occur, e.g. because of evaporation, evapotranspiration, product integration or discharge into a different drainage basin or the sea (Lundie 2010; ISO/WD 14046 2011).

This is an important distinction because, depending on how water consumption is defined, it can alter the results of the analysis significantly. Basically, this distinct definition accounts for water that, under normal circumstances, is lost within the system and can only be replenished by rains or if carried from a different location. Although an effort was made to ensure that the water consumption values were consistent with this definition, some sources may have included wastewater discharge as part of their water consumption values. For this thesis, the term “water splash”, a phrase coined by the Ford Motor Company, to represent the water consumption and/or use by products, process, and or services will be used.

## 1.5 Vehicle Life Cycle Stages

The life cycle of vehicles, like that of most other consumer products, is comprised of five main stages: 1) material production, 2) parts production, 3) production and assembly, 4) use phase and 5) end of life or disposal, as shown below in Figure 2 (Sullivan, Burnham et al. 2010). These stages focus on the major categories that would directly consume natural resources as part of a vehicle

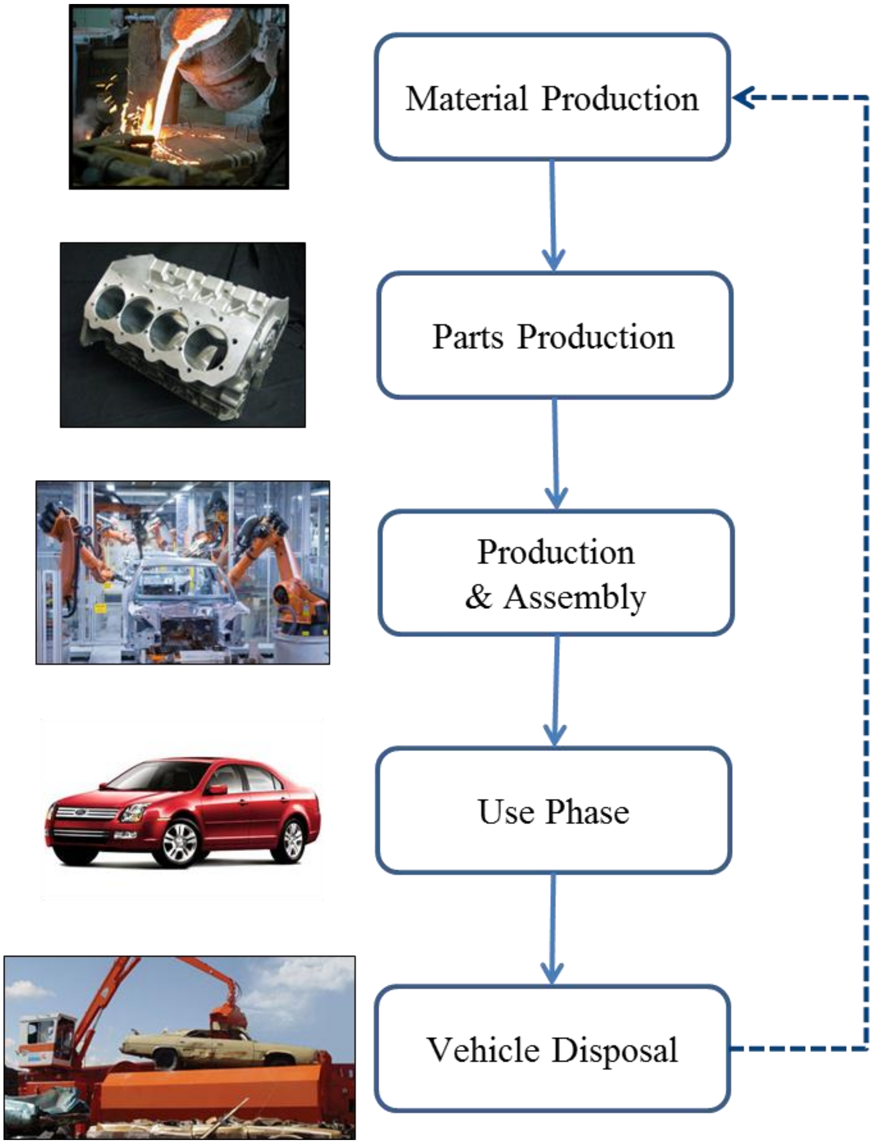

Figure 2: Life Cycle of a Vehicle (Sullivan, Burnham et al. 2010)

The material production pertains to the acquisition of raw materials and their refinement to make constituent materials that comprise a product. These processes include mining the earth for the natural resources, and all of the intermediary process required to produce a final material that can be incorporated or modified further to be incorporated into a vehicle.

The parts production deals with the processes required to produce parts, components, and assemblies used in a car, which can include casting, machining, injection molding etc. The natural resource consumption for this stage is highly variable and depends on material composition, efficiency of systems, and choices by the manufacturers.

The production and assembly is tied to the processes required by the automakers to produce the final vehicle to be sold to the customer. This can include welding, painting, and general assembly. Depending on the level of manufacturing and outsourcing, some of the processes involved may overlap with those of the parts production.

The use phase of a vehicle takes into account the driving by owners and how much natural resources are consumed to maintain the vehicle during normal operations. These burdens are dependent on parameters like the source of energy, whether its main energy sources is fossil fuels or electricity, fuel efficiency and the lifetime drive distance.

The end of life, the final stage for a vehicle, examines what happens to the product after it is no longer in use. The analysis for this phase studies the burdens associated with the scrapping and salvaging of a vehicle. These burdens include those associated with vehicle shredding, and the recovery of materials and parts.

Although many studies have been completed analyzing the various individual stages of a vehicle’s life, few have been completed focusing specifically on the water consumption. Given the rising concern about water scarcity, as explained in an earlier section, and the great number of vehicles currently being used today, it becomes a relevant matter to better understand the water consumption for a vehicle. By examining the life cycle of a vehicle, areas requiring more attention or further studying, can be identified so that proper measures can be taken to reduce water consumption which may ultimately lead to a more environmentally friendly and sustainable product.

## 1.6 Research Questions

The previous sections discussed the issue of water scarcity, the importance of water use in manufacturing and the relevance of understanding water consumption in the life cycle of a vehicle. These topics lead to one major theme or question to be answered in this thesis:

| What is the water consumption for the life cycle of a passenger vehicle? |
|---|

The goal for this thesis is to break down the each part of the life cycle of a vehicle in the major sections described in section 1.5 and to find out where water is consumed, how much water is consumed, and how this water consumption compares to the other stages. Each part of the life for a vehicle will be taken apart and examined individually with representative models that help to quantify the flow of material through the system and the water consumption for each of the processes involved. In other words, the research will also attempt to answer the following question:

| What aspect of the life of a vehicle consumes the most water? |
|---|

Breaking apart water consumption for each of the stages will help to develop a more holistic understanding for the life of a vehicle. It will also provide models to better understand areas having a greater impact and what sort of improvement or practices in production lead to a more environmentally friendly product in terms of water consumption.

## 1.7 Focus and Scope

The thesis focuses on water directly consumed in the life of a vehicle, or in a later section, indirectly in the production of energy. It ignores the water used or consumed in developing the infrastructure for any aspect for the life of a vehicle, such as the water consumed in constructing the manufacturing facilities or the indirect water consumption resulting from transportation of the components. Once the infrastructure development water consumption is considered, the water consumption for each set of raw materials for construction and also the water consumed in the intermediate processes must also be considered; such data is inconsistent. In defining this boundary, it is also assumed that the majority of the infrastructure for producing the raw materials or electricity could have existed for decades and would not be dedicated solely for the life of vehicles in the automobile industry (Yen, Zullo et al. 2011).

For the analysis, this thesis will focus on the life cycle inventory. In other words, the thesis will focus on quantifying the water consumption for the life of a vehicle rather than the impact of this water consumption as it would be done in a life cycle assessment. This is another important distinction to be made because it would change the scope of this work to include the environmental, social, and economic impacts of the water consumption associated with the life of vehicle which this thesis does not include. Rather, this thesis focuses on establishing an initial benchmark for water consumption in the life of a vehicle since no complete studies have been found up this point and in describing an approach to determining the volumetric water requirements.

Along these lines, the thesis will focus on the primary processes involved, say water used for cooling parts, rather than some of the secondary processes, like water consumption associated with the needs of the employees. Although some of the sources may have included this type of data in their assessment, an effort was made to differentiate between the two. The reasoning behind this decision is that information presented would no longer focus on the just the life cycle of a vehicle but possibly also include all water requirements to support the communities involved.

## 1.8 Approach and Methodology

Quantifying the water consumption for the life of a vehicle can be a very complicated task because of all the different materials, processes and machinery that have to be accounted for as part of the analysis. This process becomes even more challenging as a result of the great variability among procedures and practices in each stage depending on the area of operations, business model and machinery usage. So, rather than examining every single component, and attempting to trace it as it flows through the different stages, certain process generalizations on the flow of materials through each step can be made to develop a model for water consumption. The flow of materials, in terms of kilograms or percentages, is coupled with the water consumption per each process in each of the stages for a vehicle on a liter per kilogram basis to determine the overall water consumption. If a particular material experiences more than one process in a stage, then the water is added to maintain a running total of the overall consumption.

To use the general approach of following material through the life of a vehicle, the first step is to determine the appropriate material composition for a vehicle. Finding the correct material composition ensures that the right assumptions are being made and that the correct processes are being accounted for as part of the analysis. The material composition of a vehicle can then be traced going through each of the stages in the life of a vehicle to determine the water consumption. The water consumption for the flow of each of these materials as they move from one stage to the next can be calculated and used to quantify the water consumption for the life of a vehicle. Figure 3 illustrates the basic layout of the process to be used in the analysis. More detailed explanations for the methodology, boundary conditions, and assumptions, for each stage are to be provided in future chapters. Since this analysis only deals with water consumption and material flows, all other inputs and outputs will be ignored.

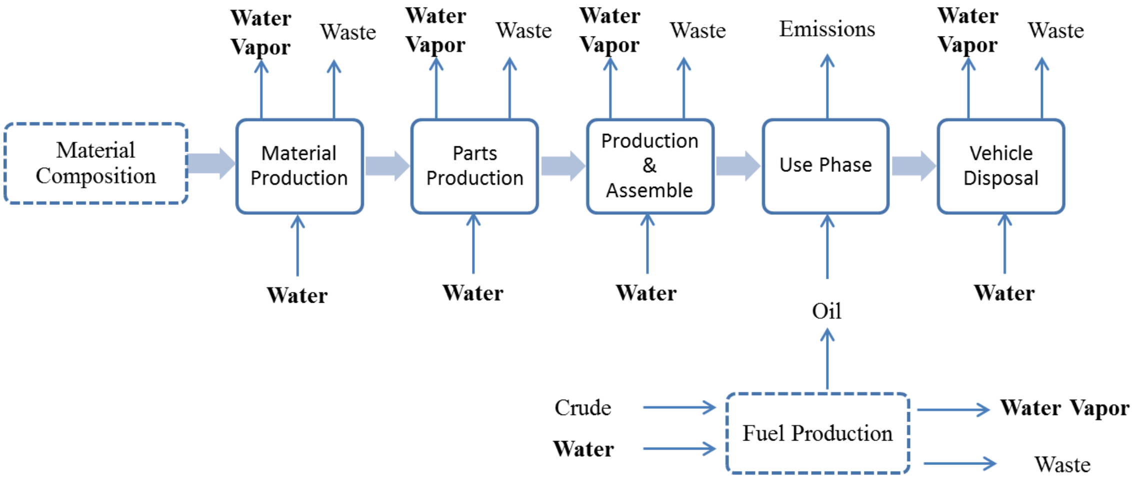

Figure 3 : Process Overview

### 1.9 Material Composition

As mentioned before, the first step in developing the assessment for water consumption as part of a vehicle is to find an appropriate material composition for a vehicle. A very detailed differentiation of the materials is not as important because the processes can be simplified and coupled for different materials. However, a reasonable vehicle composition must be identified so that proper values can be attributed to the various processes. Given the importance of having the correct material composition, multiple sources were compared which listed the information from various locations. The comparison of the data allowed for a better understanding of the type and quantity of materials that make up an average vehicle.

A study on the life cycle analysis of passenger cars by (Spielmann and Althaus 2007) provided the average weight of passenger vehicles sold in Switzerland. The researchers investigated the environmental burdens of car infrastructure by expenditures for fuels and operating materials. This data was not used because the average weight for a vehicle is different in Europe (Spielmann and Althaus 2007).

In (Schmidt 2006), information is given for the typical weight composition of a New Ford Galaxy 2.0 I DW10. Like the paper on Swiss passenger vehicles from (Spielmann and Althaus 2007), the materials composition described in (Schmidt 2006) did not provide details for the different types of metals. The main reason for not using this material composition in the analysis is because it did not represent the average weight of a U.S. vehicle.

Much more comprehensive data for average size automobiles in the United States was found in (Das, Curlee et al. 1995). Their data is used in this assessment mainly because it better represents the typical weight for a U.S. vehicle. Although their model provided detailed descriptions for the different kinds of metals and plastics, they were simplified for the assessment so that materials could be more easily coupled with different processes (Das, Curlee et al. 1995).

Finally, additional data points were collected from the U.S. Geological Survey. Their research found that the typical weight of a US vehicle was 1470 kg in the year 2004. According to their investigation, a vehicle contains 131 kilograms of aluminum and 975 kilograms of iron (Buckingham 2005). These additional data points were used to help validate the other studies.

As can be seen in Table 2**,** the values for the U.S. vehicles from (Das, Curlee et al. 1995) are in the same magnitude as the values for both the Swiss passenger vehicles (Spielmann and Althaus 2007) and the New Ford Galaxy 2.0 DW10 cDPF Trend edition (Schmidt 2006). Depending on which vehicle is chosen, the material composition would vary so the water consumption for each vehicle would differ. The water consumption per kilogram of material would be in the same magnitude regardless of which vehicle is selected as they would go through the same processes.

Table 2: Comparison of Automobile Material Composition (Das, Curlee et al. 1995; Schmidt 2006; Spielmann and Althaus 2007)

| **Material** | **Swiss Vehicle Percentage (Spielmann and Althaus 2007)** | **Swiss Vehicle Weight (kg)** | **U.S. Vehicle Weight (lbs.) (Das, Curlee et al. 1995)** | **U.S. Vehicle Weight (kg)** | **Ford Galaxy 2.0 Weight (kg) (Schmidt 2006)** |
|---|---|---|---|---|---|
| Iron | 0% | 0 | 429.5 | 194.8 | |
| Steel | 0% | 0 | 965 | 437.7 | |
| High Speed Steel | 0% | 0 | 247 | 112 | |
| Stainless Steel | 0% | 0 | 41.5 | 18.8 | |
| Other Ferrous | 0% | 0 | 67 | 30.4 | |
| Ferrous | 73.70% | 990.5 | 1750 | 793.8 | 1034 |
| Aluminum | 3.90% | 52.4 | 340 | 154.2 | |
| Copper | 0% | 0 | 45 | 20.4 | |
| Zinc | 0% | 0 | 16 | 7.3 | |
| Non-Ferrous | 2.40% | 32.3 | 0 | 0 | |
| Other Metals | 6.30% | 84.7 | 401 | 181.9 | 194 |
| Fluids | 0.40% | 5.4 | 177 | 80.3 | 27 |
| Glass | 2.20% | 29.6 | 88 | 39.9 | 48 |
| Plastics & textiles | 17.40% | 233.9 | 400 | 181.4 | |
| Rubber | 0% | 0 | 133 | 60.3 | |
| Plastics &Elastomers | 17.40% | 233.9 | 533 | 241.8 | 355 |
| Other | 0 | 0 | 96 | 43.5 | 0 |
| Total | 100.00% | 1344 | 3045 | 1381.2 | 1658 |

It should be noted that based on the ways materials are handled during each stage for the life for a vehicle, a slightly modified version for the U.S. vehicle weight will be used. The materials will still be present, but they may be coupled with other materials of similar properties if they are processed together. The appropriate assumptions for the material composition for each part of the life of a vehicle will be explained for each part of the life for a vehicle in each chapter.

## 1.10 Data Sources & Uncertainty

Four main sources were used to determine the water consumption in the life for a vehicle: published papers, government reports, publicly available company information in the form of product description and environmental reports, and EcoInvent V2.2 to compare the water consumption to the water use. In each chapter dealing with the life cycle analysis, we will discuss the sources use and what sorts of values were provided by each to determine the water consumption. Different aspects of the sources became important for different stages.

In addition to selecting valid sources, an effort was made to ensure that the definition and scope mentioned in the work was consistent with the water consumption described earlier. Finding such sources proved challenging because many of the sources did not provide a definition for water consumption nor did they describe the specific processes that led to the given value.

Despite efforts to ensure the use of quality data, uncertainties and limitations of data are inevitable and thus restrict a specific interpretation of results. As will be later shown, even when the source of the data is valid, and the definition for water consumption is consistent with that given in this thesis, there is still a great deal of variability for the values. The differences in values can be the result of a great many factors, such as more or less efficient machinery, open or closed cooling systems, or even more cleaning required to meet certain quality expectations. What is more important than an exact water consumption number, is the magnitude for water consumption and the general trends of areas requiring more resources as it will later be shown.

# CHAPTER 2:

# BACKGROUND AND LITERATURE REVIEW

## 2.1 Product Water Footprint

Previous research and life cycle inventories have focused on water consumption on a regional or national scale as well as in certain goods, services, and materials. Many of these studies have focused on the concept of the water footprint. Professor Arjen Y. Hoekstra first defined the term "water footprint" in 2002 in order to quantify the amount of water used not only directly from a consumer or producer/manufacture but also from indirect water usage. The water footprint of a product is the volume of freshwater used to produce the product, measured over the entire life. It is a multi-dimensional indicator, showing water consumption volumes by source (Hoekstra, Chapagain et al. 2009). Water foot printing is a useful tool to build awareness of the water used in the value chain to produce the products we consume (Hoekstra, Chapagain et al. 2009). In the analysis, all processes within a production system that significantly contribute to the overall water footprint need to be accounted for. If one traces every aspect of a product, one will see that the impacts of the process all interconnect with other products and that links are never-ending. In practice, however, there are only a few process steps that substantially contribute to the total water footprint of the final product. (Hoekstra, Chapagain et al. 2009). By breaking down the life of a vehicle, and determining the water consumption for each process, a picture showing the environmental impact of each can be develop to better assess the total water consumption for the life of a vehicle.

Water footprints have been quantified for commodities ranging from agricultural and bioenergy crops and have extended to regional scales. For example, Hoekstra and Chapagain have assessed and analyzed the aggregate water footprints for a series of countries, from which they examine the internal (domestic) water footprint along with any water footprints from imported commodities or services across agricultural, industrial, and residential/domestic sectors; this study was conducted across a selected group of countries ranging from The Netherlands to the U.S. to China. From this assessment, the authors determined that, on a national scale, the total water usage in the United States from 1997 to 2001 was 696 $Gm^3$ per year (2483 $m^3$ per capita per year) while the total water consumption for India at the same time period was 987 $Gm^3$ per year (980 $m^3$ per capita per year) (Hoekstra, Chapagain et al. 2009). Based on these values, they found that the water footprint for a specific country or region was dependent on four factors: volume of consumption, consumption pattern, climate, and irrigation. From there, they examined variations between these countries – for example, the higher water footprint per capita in the U.S. was found to be due to large meat consumption and industrial products consumption, while arid regions had higher water footprints due to lower crop productivity and evapotranspiration. Hoekstra and Chapagain also point out several approaches to reducing water footprints for certain regions, such as for adopting less water-intensive production techniques for industrial processes, shifting product consumption patterns (such as reducing meat consumption), and transferring production processes or water-intensive agriculture and livestock from water-stressed regions to countries with abundant water resources (Hoekstra, Chapagain et al. 2009).

For most businesses, the water footprint in their supply chain, which includes production of materials and manufacturing of parts, is much bigger than the water footprint of their own operations; ignoring the supply chain component may lead to investments in making improvements in the operational water use while investments in improving the supply chain could have been more cost effective. This is particularly relevant in the automobile industry where the biggest companies buy most components ready to be assembled and incorporated into their vehicles. Depending on the purpose of a particular study, however, one can decide to include only the direct or indirect water footprint in the analysis (Hoekstra, Chapagain et al. 2009). In order to calculate the water footprint of the final product in a production system, one can best start calculating the water footprints of the most original resources, where the supply chain starts, and then calculate, step-by step, the water footprints of the intermediate products, until one can calculate the water footprint of the final product. The first step is always to obtain the water footprints of the input products and the water used to process them into the output product. The total of these components is then distributed over the various output products, based on their product fraction and value fraction (Hoekstra, Chapagain et al. 2009). Identifying which portions of the supply chain are the most water-intensive, whether that is raw materials or entire assemblies, allows a company to know its indirect water consumption and to better assess the business risk associated with using different suppliers in potentially water-stressed areas or ecologically sensitive regions (Morrison, Morikawa et al. 2009).

The water footprint for the use phase is in some ways simpler to calculate and in other respects much harder to determine. It is simpler to calculate because once the water footprint for the origin of energy, which is mostly made out of fossil fuels, is coupled with fuel efficiency and the total driving distance, a picture of total water consumption can be developed. This provides a good estimate of the water footprint which can be compared to other phases for a vehicle. However, the difficulty in determining this aspect of the water footprint lies in the variability of sources, applications, and processes utilized, which can create many differences in expected water consumption values.

For the end of life, the water footprint can be determined more directly by simply following a vehicle as it is exposed to the various processes and is disposed of in a fashion that meets government regulations, or is recycled. These processes tend to have fewer steps involved, which makes them easier to analyze from a water consumption perspective.

Ultimately many tools will be required, as a water footprint by itself does not provide all answers or solutions, but it provides a better understanding of absolute volumetric needs, the opportunity costs of the water used, and the impacts to environments and people that could become material risks. For companies the water footprint begins to tell an important story of dependence and risk, which can help to bring about the type of changes necessary for delivery of sustainable and equitable water management (SABMiller and WWF-UK 2009).

## 2.2 Industry Water Studies

Several companies and organizations are becoming increasingly aware of the potential issues and risks associated with water shortage and so are taking steps to measure and reduce their use. For instance, selected companies from the FTSE Global Equity Index Series (Global 500), the Australian Securities Exchange (Australia 100) and the Johannesburg Stock Exchange (South Africa 100) were invited to respond to the second annual CDP Water Disclosure information request because they operate in sectors which are water-intensive or exposed to water-related risks (Delloitte 2011). The majority of responding companies have identified water as a substantial risk to their business and almost two thirds of companies have identified water-related opportunities and most opportunities are reported as near-term (Delloitte 2011). In other words, they have identified opportunities including cost reductions associated with increased water efficiency, revenue from new water-related products or services, and improved brand value.

Companies like Ford Motor are already working to limit their impact in a water stressed region. For the past few years, the Mexican state of Chihuahua has suffered droughts caused by below average rainfall. As a result, the Rio Grande River that supplies the region is unable to support increasing development and a growing population. As water resources became stressed at the Ford Motor Chihuahua Engine Plant (CHEP) in Chihuahua City, the company investigated ways to reduce water use and limit impact to the surrounding community. Six years ago, Ford Motor began making changes in its manufacturing process at CHEP; today, the plant uses no potable water except for human consumption (Delloitte 2011).

Strategies to reduce the intensity are not only becoming common amongst fabricators of industrial products but also among manufactures of consumer goods. For instance, Puma determined that 99.9% of their water consumption came from their global supply chain, of which 89% was consumed in either Tier 3 or 4.

Other big corporations have also taken steps to not only quantify their water intakes but also developed plans to reduce it. Coca-Cola Company, for example, launched global water strategies to address water management at each of the company’s 900 bottling plants and that extends outside operations to include watershed protection, supporting sustainable communities, and helping raise awareness and inspire action around global water challenges.

Even IT companies are realizing the importance of managing water (Delloitte 2011). Cisco Systems worked with three printed circuit board assembly partners to dramatically reduce water use in processes for Cisco Systems products. Up to 20 million gallons of water was being used each year to wash the printed circuit boards after they were soldered. By implementing a new soldering practice, the wash stage of the process became unnecessary. This led to a significant reduction in the amount of wastewater that was produced and that required treatment and disposal. Cisco Systems set out to eliminate this process in mid-2010 and achieved that goal in 2011

As can be seen many companies are focusing on reducing water use and water consumption through a variety of approaches. They understand the risks associated with not taking action on this important matter, and see the long term benefits in becoming more efficient in how they use resources and manage their operations.

## 2.3 Cost and Financial Benefits of Reducing Water Usage

Reducing water usage during their operations can help companies in a variety of ways. First, it can help them by creating a better brand which often attracts new customers and retain old ones by advertising a better environmental track record. Secondly, it helps to establish a better relationship with the surrounding community which helps their continued operations within that area. Thirdly, it can help to better meet government regulations which can avoid fees. And, of similar importance, it has monetary benefits. The reduction of water usage can attract further government financial incentives and reduce costs which improve the bottom line, and can also help the community as a whole by fostering economic development.

### 2.3.1 Cost of Water

One of the major drivers behind taking steps to reduce water use and water consumption can be cost reductions. Simply using water once and discarding is a very inefficient way of operating, especially if the cost of water in an area is high. So to better understand the financial drivers that may motivate some businesses to reduce the water footprint, we researched the cost of water. This would help us to better determine if introducing water saving technologies would actually be financial beneficial for companies. A summary of various prices of water and waste water services across the countries world, and some specific cities, can be found below in Table 3. As it can be seen, there is a great deal of difference associated with the cost of water and wastewater services for different area.

Table 3: Prices of Water and Wastewater Prices (USD / m^3) (2008; Gurría 2009)

| Location | Cost |
|---|---|
| Cork (Ireland) | 0 |
| Colombo (Sri Lanka) | 0.02 |
| Chennai (India) | 0.15 |
| Buenos Aires (Argentina) | 0.27 |
| Yerevan (Armenia) | 0.57 |
| Mexico | 0.69 |
| Acapulco (Mexico) | 0.50 |
| Korea | 0.82 |
| Italy | 1.20 |
| Japan | 1.38 |
| Greece | 1.45 |
| Athens (Greece) | 1.57 |
| New Zealand | 1.69 |
| Australia | 1.99 |
| Amadora (Portugal) | 2.30 |
| Detroit (USA) | 1.83 |
| Finland | 2.78 |
| Sweden | 2.82 |
| Hungary | 2.93 |
| Budapest (Hungary) | 2.86 |
| England and Wales | 3.15 |
| France | 3.16 |
| Singapore (Singapore) | 3.43 |
| Denmark | 4.41 |
| Copenhagen (Denmark) | 8.69 |
| Scotland | 9.45 |

The data found points to three major points in terms of costs. First, it shows that water is not usually a very costly natural resource and thus may not necessarily provide enough incentives to introduce more efficient and effective technologies and practices. This may be the case if the input and output flows for particular operations are not very high and if the costs of other resources, like electricity and natural gas, are more expensive. However, in operations having a very high flow rate, it may actually save the company enough money to pay for the initial investment costs. Secondly, the data points to the fact that whether or not costs are a driving factor for a company to make improvements, is a highly localized matter. In other words, in terms of cost, a company may not save any money in Sri Lanka where the cost of water is almost zero, but may have significantly more savings in Denmark, where the cost of water may be $4 or more dollars per meter cubed. And thirdly, it shows that the cost of water is not necessarily associated with availability or economic development of a country. Although the cost of water does appear to be generally higher in industrialized nations, there are some clear exceptions like Cork, Ireland that does not charge for its water. A graphical representation of the data can be found below in Figure 4.

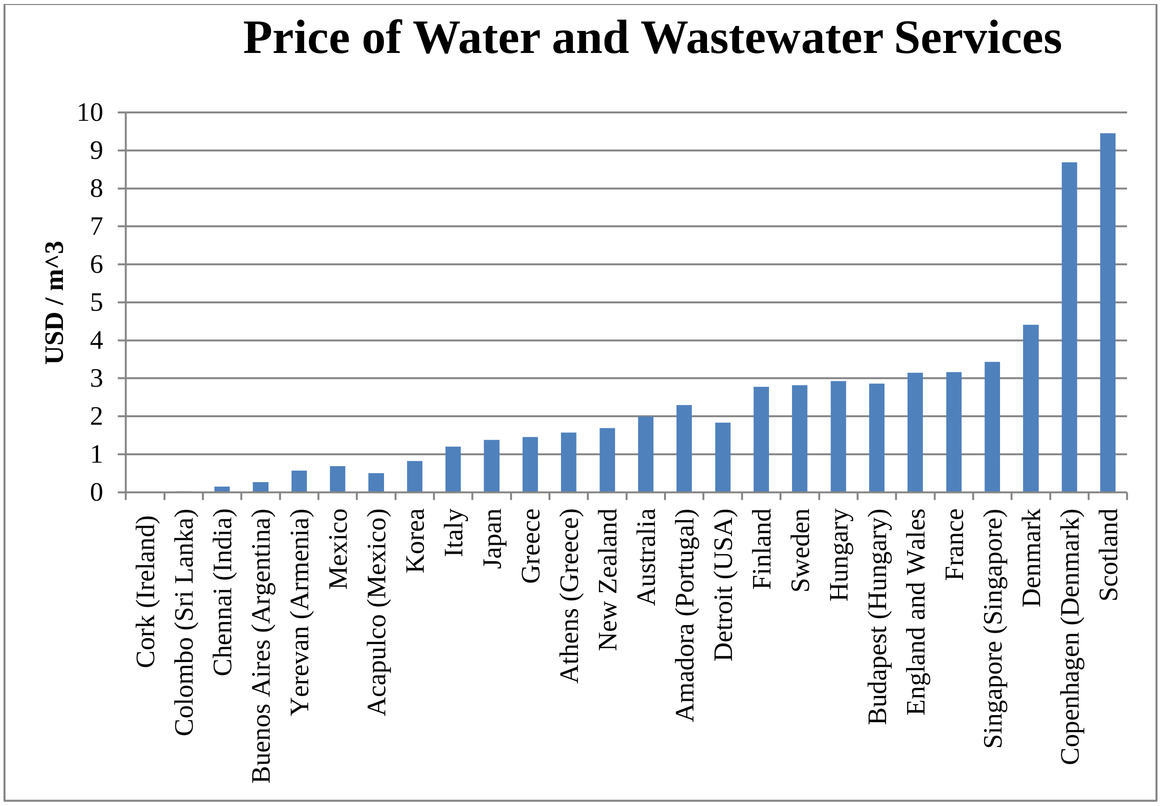

Figure 4: Prices  of Water and Wastewater Prices (2008; Gurría 2009)

It should be noted that the price of water is not always higher or lower than the price of wastewater services. In some instances, the price of water for different applications commercial, residential, or industrial also differs depending on the regulations and applications for each city (CWSD 2011; PWSA 2012). This trend can be seen by examining the water data shown in Table 4 Table 5 for Detroit, which charges more for sewage treatment than for water input, and Pittsburgh, which charges more for water than for sewage treatment (CWSD 2011; PWSA 2012). More than being driven directly by actual cost to purify and treat water, different cities or even different countries, may assign a cost based on policy. Perhaps in order to attract businesses, the city of Pittsburg decided to offer preferred costs to industrial applications, or perhaps they can provide cheaper services when the flow rates are higher.

Table 4: Cost of Water for Detroit, MI (CWSD 2011)

| | 1,000 cubic feet | 1,000 Liters |
|---|---|---|
| Intake (USD) | 14.85 | 0.52 |
| Sewage (USD) | 36.95 | 1.30 |
| Total | 51.8 | 1.83 |

Table 5: Water Cost for Pittsburgh, PA (PWSA 2012)

| | 1,000 gallons | | | 1,000 Liters | | |
|---|---|---|---|---|---|---|
| | Water Allocation | Sewer Treatment | Total | Water Allocation | Sewer Treatment | Total |
| Residential | 8.48 | 2.82 | 11.3 | 2.24 | 0.74 | 2.99 |
| Commercial | 8.13 | 2.61 | 10.74 | 2.15 | 0.69 | 2.84 |
| Industrial | 7.62 | 2.57 | 10.19 | 2.01 | 0.68 | 2.69 |

Going beyond cost savings for a particular area, a company may still need to take steps to reduce their water footprint whether or not it makes sense financial, at least from a directly quantifiable and measurable number in their balance sheet, for other reasons, as described in section 1.3. Taking steps to reduce their water footprint may be a way for businesses to reduce their resultant business risk, especially in areas experiencing water scarcity. It is a way for them to develop better relationships with the surrounding communities so that they can continue doing business, whether that be in manufacturing, or maintaining any other kind of facility in the area. Reducing their water footprint is also a way for companies to ensure that they continue to meet government regulations and thus avoid fees and potentially limitations in their future growth.

### 2.3.2 Government Incentives

Many localities experience water droughts are trying to reduce their depending on natural resources by promoting more efficient practices. This can extend from providing tax breaks for improvements, to providing free services, to actually paying companies themselves for water savings. Examples of different programs across the U.S. can be found below for the state of Colorado, Georgia, and even Washington, which is not often associated with water scarcity (Denver Water 2012; Georgia Enviromental Finance Authority 2012; Saving Water Partnership 2012).

Denver Water, which provides access to 1.3 million people in the city of Denver and many surrounding suburbs, is Colorado's oldest and largest water utility, has partnered with the U.S. Environmental Protection Agency for WaterSense, a national program that makes it easy to choose products that use less water without sacrificing quality or product performance (Denver Water 2012). Denver Water also has a program that will pay commercial, industrial and institutional customers $18.50 for each thousand gallons of water saved annually, but they must save at least 100,000 gallons of water in one year. With these incentive contracts, customers can earn 50 percent of project cost up to $40,000 for conserving water. This includes everything from Denver Water’s Cooling Tower Incentive Program, Denver Water which pays business to make cooling tower more water-efficient, to offering a $75 rebate to commercial customers who install WaterSense high-efficiency toilets that use an average of 1.28 gallons per flush or less. And lastly, they even send out conservation technicians and engineers to facilities to identify all water-using fixtures and processes for free (Denver Water 2012).

The Georgia Environmental Finance Authority (GEFA) facilitates programs that conserve and improve Georgia's water resources. GEFA provides loans for water infrastructure amongst other programs. They offer GEFA offers flexible and accessible low-interest loan programs, and exceptional customer service. In the last five years, GEFA has financed more than $65 million in water-efficiency and conservation projects. As a result of the Green Project Reserve in the SRF programs, GEFA has provided greater amounts of water-efficiency financing and provided substantial additional subsidization for these (Georgia Enviromental Finance Authority 2012)

Saving Water Partnership is a group of local utilities that fund water conservation programs in Seattle and King County. The offer a great deal of financial incentives for water reduction upgrades for commercial and industrial applications. For instance, they provide $100 per-toilet rebate for replacing old toilets with WaterSense labeled 1.28 gallon toilets in apartments or condos with 4 or more units. They even provide rebates for up to 50% of costs for projects involving water-cooling of industrial processes. This is surprising because the area around Seattle is now typically associated with water scarcity (Saving Water Partnership 2012).

As it can be seen, different states in the U.S. have different approaches to promoting water conservation. Some provide actual refunds while others facilitate the development of improvements by giving loans. Regardless of the approach, it can be seen that companies have government financial incentives and assistance to help reduce their water consumption rates.

### 2.3.3 Economic Development

Going beyond the actual costs and savings for companies, making improvements to save water can actually have a quantifiable benefit to communities by fostering economic development. The Alliance for Water Efficiency, a broad-based non-profit organization dedicated to the efficient and sustainable use of water in the United States and Canada, completed a study to determine the financial benefits for society as a whole that result from water improvements. Their report quantitatively examined the short-term economic growth impacts of water/energy efficiency investments, specifically in terms of job creation, income, GDP, national output, water savings, and other benefits (David Mitchell, Thomas Chesnutt Ph D. et al. 2008)

Their consultants examined wide range of water/energy efficiency program possibilities, across all water-using sectors commercial/industrial/institutional involving indoor, outdoor, and water system efficiencies. This modeling showed that economic stimulus benefits could be distributed throughout the economy. The economic output benefits range between $2.5 and $2.8 million per million dollars of direct investment. GDP benefits range between $1.3 and $1.5 million per million dollars of direct investment. Employment potential ranges between 15 and 22 jobs per million dollars of direct investment. Thus, direct investment on the order of $10 billion in water/energy efficiency programs can boost U.S. GDP by $13 to $15 billion and employment by 150,000 to 220,000 jobs and could save between 6.5 and 10 trillion gallons of water, with resulting energy reductions as well. In other words, by investing in saving water technologies, a community can see some significant economic improvements (David Mitchell, Thomas Chesnutt Ph D. et al. 2008).

## 2.4 Previous Studies: Vehicle Life Cycle Inventory

Many studies have been conducted on the life cycle of a vehicle. However, few have focused on water consumption. Most published papers focus on energy consumption, carbon emissions, solid waste, and emissions to water. Few mention water use, or water consumption. These papers do provide a general approach to existing life cycle inventory methodologies which can also be used determine the vehicle splash. They also provide expected trends for the environmental burdens in terms of energy consumption and carbon dioxide emissions which can be compared to water consumption.

Amongst the few studies that actually included water in any form in their analysis was a report by Volkswagen focused on the 10 year life-cycle inventory of four VW Golf A4 variants (ranging from 800-1,181 kg curb weight). The report provides detailed assumptions and results on water use and consumption (Schweimer and Levin 2000). The authors report that "water consumption of 95 $m^3$ (95,000 liters) per car can be broken down into that needed for electric power generation (46 $m^3$), fuel production (23 $m^3$), car washing (8 m3), material production (10 $m^3$) and other factors (9 $m^3$)" (Schweimer and Levin 2000). The authors also commented on a lack of references against which comparisons can be made. Specifically, the authors wonder whether 8 $m^3$ of water used during the 10-year use phase for car washing is excessive or below average (Schweimer and Levin 2000). This report has several points that make it an important guidance for future work. First, it points to fuel production as the biggest direct consumer of water for the life of a vehicle, and also, the report points to power generation as the actual biggest consumer of water, even if it is an indirect part of the life for a vehicle.

Other more detailed studies like the one completed for Nissan in Japan focused on energy consumption and carbon emisions, Figure 5 and Figure 6, and provided an approach to determine the enviromental impact for the life of a vehicle (Kobayashi 1997). In this study, a vehicle having a body weight of 1270 kg, a running distance of 94,100 km, fuel consumption 10.8 km / liter is examined. The body weight was broken down in detail to include the material composition by differentiating amongst different types of metals and plastics. The paper focused on mining and producing materials, parts and automobile production, operation, maintenance, and disposal and recycling. Basically, it had all the parts described earlier which are to be examined as part of the splash for the life cycle inventory of a vehicle (Kobayashi 1997). It even included specific process like machining and forging in the production of parts. What was interesting about this study is that, similarly to the report written by Volkswagen, it pointed to the use phase or operation of a vehicle as having the biggest environmental impact.

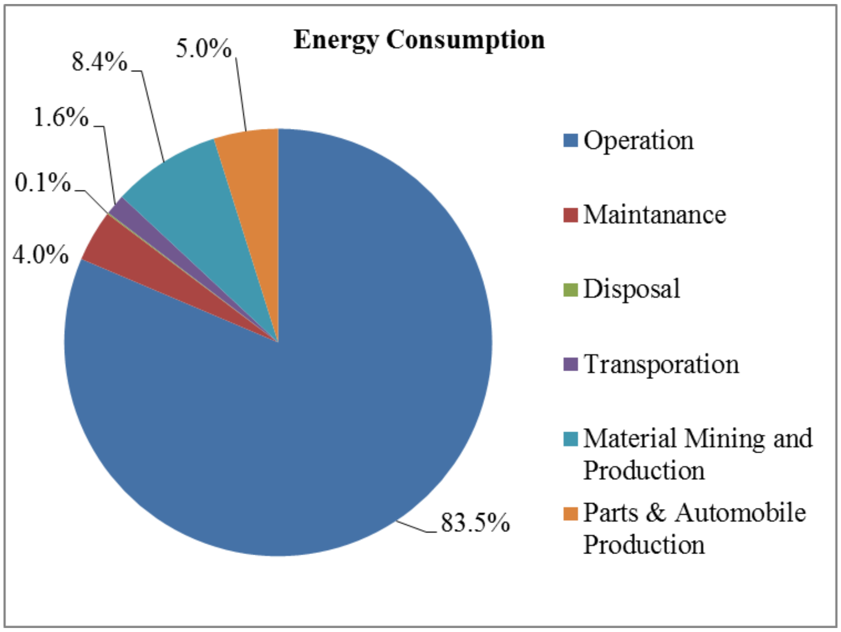

Figure 5: Energy Consumption (Kobayashi 1997)

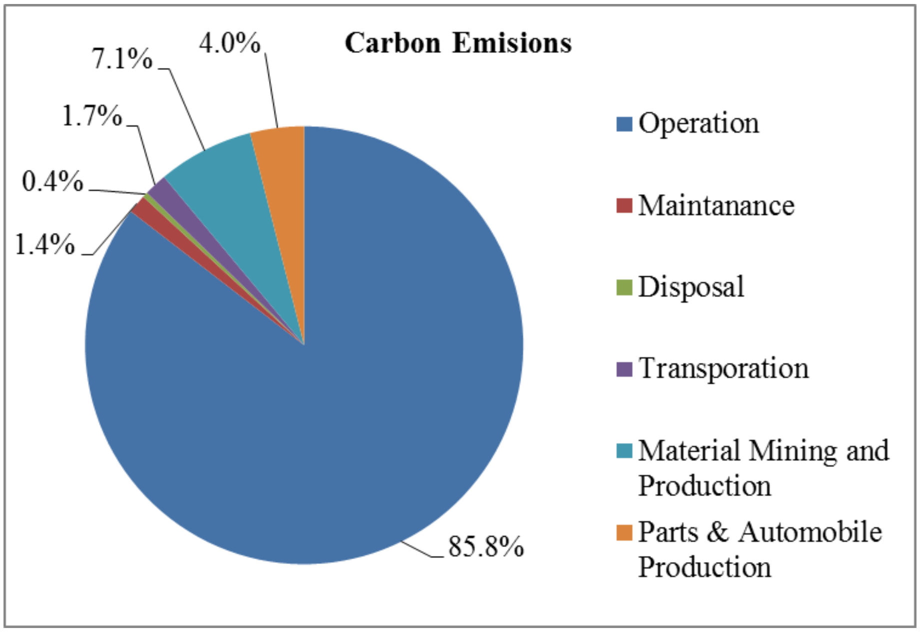

Figure 6: Carbon Emissions (Kobayashi 1997)

A final paper was examined which provided a summary and a comparison on nine published full vehicle life cycle inventory studies. The paper went in depth to compare the various studies of energy consumption, carbon emission, and other environmental impacts like solid waste from the different sources. Basically, all previous studies completed up to that point were examined to establish a variability among the existing data (Sullivan and Cobas-Flores 2001).The paper discussed the major aspects for the life of a vehicle: materials production, parts and product manufacture, operations and maintenance, and end of life. The paper found that most of the environmental burden of the vehicle was related to the use phase. Another key aspect of the information in the paper, or rather the lack of it, was the fact that water consumption or water use was not mentioned in any way. Water emissions were included, but this referred to the contaminants added to the water (Sullivan and Cobas-Flores 2001).

There are three general trends that can be seen by examining previous work on the life cycle analysis for a vehicle. First, most deal with energy and emissions rather focusing on water consumption. The lack of inclusion of any water use or water consumption data is unclear. Most of the studies seem to have been conducted in areas that may not necessarily experience yearly periods of water scarcity so water consumption may not have be seen as important. Second, previous studies point to the use phase as having the biggest environmental impact when compared to the other phases for the life of a vehicle. And lastly previous studies show that water consumption data is lacking.

# CHAPTER 3:

# MATERIAL PRODUCTION

## 3.1 Scope

The assessment in the material production stage for the life of a vehicle will only include water used and water consumed for the production of raw materials and semi-finished products. It is assumed that the materials from this stage need further processing before being incorporated into the vehicle. This stage accounts for the direct extraction of materials that are to be processed, along with other recyclable materials, to a point where they can be shipped to manufacturers. A summary of the scope for this stage in the life of a vehicle can be shown below in Figure 7.

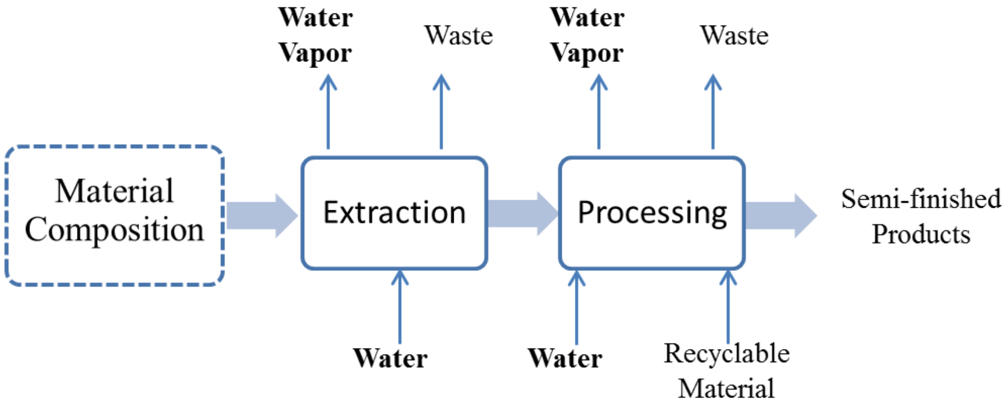

Figure 7: Material Production

## 3.2 Material Composition

A modified version of the material composition presented earlier, Table 2, will be used as a basis to determine the water consumption in the production of materials as shown in Table 6. In other words, this chapter will focus on determining the water use and then the water consumption for these materials. Iron and steel are combined into one section because of the similarities in producing both materials. Some of the plastics are separated because they undergo different processes to produce the raw materials. Some of the materials were removed because they either are not relevant for this stage or no information is given from the original source on material composition to explain what these materials could be.

Table 6: Simplified Material Composition (Das, Curlee et al. 1995)

| Material | Kg |
|---|---|
| Steel | 793.8 |
| Aluminum | 154.2 |
| Copper | 20.4 |
| Zinc | 7.3 |
| Rubber | 60.3 |
| Glass | 39.9 |
| ABS | 24.9 |
| Nylon | 11.3 |
| Polyester | 12.2 |
| Polyethylene | 16.3 |
| Polypropylene | 21.3 |
| Polyurethane | 44.0 |
| Polyvinyl chloride | 12.7 |
| Magnesium | 43.5 |
| **Total** | **1262.4** |

### 3.3 Literature Review

Before starting the supply chain water consumption analysis focusing on the material production, a literature review was completed to determine existing water models. Most authors were not concerned with the water consumption, but chose to focus on either carbon dioxide emissions or energy use. In some cases, the data found did provide information on water use for different materials as part of the supply chain, but did not offer any further description of the scope of the analysis used to calculate these values (Hischier 2007; Classen, Althaus et al. 2009). Saari determined that the typical water consumption for a vehicle was 90,100 liters for the production of materials, and 242,000 liters for the whole vehicle. However, no information was provided to indicate where and how water was used or even if water was recycled. In other the study gave was no scope for the analysis and no clear definition of water consumption (Saari, Lettenmeier et al. 2007).

## 3.4 Data Sources

An effort was made to ensure that the data used was from sources that were either tied to industry, published in an academic journal, or from a government agency. The data, collected for water consumption for steel and aluminum were gathered from the U.S. Department of Energy (Margolis and Sousa 1997; Margolis and Brindle 2000). Although these values can vary depending on interpretation, and even depending on which processes are assumed in the analysis, the values selected were from the more commonly used processes.

The values for some of the other materials, like copper, zinc, magnesium and glass were obtained from sources like the U.S. Department of the Interior or from published work in the International Journal of Life Cycle Analysis (BCS Inc. 2002; Xiao, Songwen et al. 2003; Pulselli, Ridolfi et al. 2009; Du, Han et al. 2010).

The data obtained for plastics and rubber were obtained from either publicly available data provided directly by manufacturers or from professional associations (Bridgestone 2010; Franklin Associates 2010).

Finally, EcoInvent V2.2 was also used to create an alternative model based on water use. In the reports, water use  was not clearly identified but it seemed to describe how much water was measured going into a process without taking into account recycling or without mentioning how the water could be discharge back to its original source  (Hischier 2007; Classen, Althaus et al. 2009).

### 3.5 EcoInvent Database

As an initial assessment of the water values, the recorded water values from the EcoInvent Database as shown in Table 7 were located. Although the data obtained from the reports in the data base did not contain descriptions of how the water was being used, or how much water was consumed, it provided a comparison of the existing trends (Hischier 2007; Classen, Althaus et al. 2009). Table 7 also lists the record number showing where the data was stored in the EcoInvent database (V2.2). The database includes various water inputs, specifically:

- Water, cooling, unspecified natural origin
- Water, lake
- Water, river
- Water, salt, ocean
- Water, salt, sole
- Water, turbine use, unspecified natural origin
- Water, unspecified natural origin
- Water, well, in ground.

The database does not contain any water output or waste water data. Clearly, the EcoInvent data represents water use rather than consumption. Although no detailed explanation could be found regarding the origins of the “turbine water” listed, it was assumed that this water used in hydropower production of electricity for the materials. In order to remain consistent, water used for turbines was therefore not included in the following analyses using EcoInvent data. The values in table 3 refer to extraction of materials and processing of those into semi-finished products. The definition of semi-finished product is not clearly defined, however.

Table 7: Water Inputs based on EcoInvent Database

| Material | EcoInvent (liters/kg) | EcoInvent Record Number |
|---|---|---|
| Steel (Raw Material) | 31 | #1154 |
| Steel (Processing) | 55 | #8310 |
| Steel Total | 86 | |
| Aluminum (Raw Material) | 106 | #1057 |
| Aluminum (Processing) | 97 | #8312 |
| Aluminum Total | 203 | |
| Copper (Raw Material) | 198 | #1084 |
| Copper (Processing) | 66 | #8339 |
| Copper Total | 264 | |
| Zinc (Raw Material) | 40 | #344 |
| Rubber (Processing) | 120 | #1847 |
| Glass | 14 | #806 |
| ABS | 178 | #1817 |
| Nylon | 186 | #1821 |
| Polyester | 248 | #1674 |
| Polyethylene | 32 | #1829 |
| Polypropylene | 43 | #1834 |
| Polyurethane | 380 | #1838 |
| Polyvinyl chloride | 609 | #1842 |
| Magnesium | 475 | #1106 |

## 3.6 Production of Metals

### 3.6.1 Steel

The data, collected for water consumption in steel production, was gathered from a report for the U.S. Department of Energy (Margolis and Sousa 1997; Margolis and Brindle 2000). The report “Energy and Environmental Profile of the U.S. Iron and Steel Industry” described the entire steel making process from the raw materials to a semi-finished product. Although it mostly focused on energy consumption, it also explain typical water flow rates for the different steps along with recycling rates using the best available technology and acceptable discharges to meet EPA standards. Additional sources were used to help describe the processes based on gaps from the report (Margolis and Sousa 1997; Margolis and Brindle 2000).

Steel can be broken down into three basic categories: carbon steel, low alloy steel and high alloy steel (Dahlström and Ekins 2006). For this assessment, however, steel was treated as one material. Water is an important commodity for the steel and iron industry because it is an integral part of the steelmaking process. Water is used to cool equipment, furnaces, and intermediate steel shapes, to remove scale from steel products, as a source of steam, as a medium for lubricating oils and cleaning solutions, and in wet scrubbers for air pollution control (Margolis and Brindle 2000) Although a large amount of water is typically cited as a requirement to produce steel, this figure includes recycled and reused process and cooling water (Ellis, Dillich et al. 2000). Much of the water used at steel plants is not consumed but is reused and recycled. Currently, over 95% of the water used for steel production and processing is recycled (Margolis and Brindle 2000). This is an important distinction because it helps to determine the true water consumption to produce steel. A detailed description of the processes involved in producing the raw material is given APPENDIX A (Margolis and Brindle 2000). A summary of the steel making process can be found in Figure 8. A summary showing the water consumption values for the steps necessary to produce steel can be found in Table 8. The government report used to obtain these values of water consumption in gallons per ton, but they were converted to liters per kilogram of material produced to make the result consistent with the rest of the results given throughout the thesis.

Figure 8: Steel making process (Margolis and Brindle 2000)

Table 8: Summary of steel production (Margolis and Brindle 2000)

| Process | Gallons/Ton | Liters/Kg |
|---|---|---|
| Coke Making | 220 | 0.83 |
| Iron Making | 120 | 0.45 |
| Electric Arc Furnace | 120 | 0.45 |
| Vacuum Degassing | 110 | 0.42 |
| Continuous Casting | 25 | 0.09 |
| Hot Forming | 72 | 0.27 |
| Pickling | 260 | 0.98 |
| Cold Forming | 20 | 0.08 |
| Total | 947 | 2.89 |

Combining the water consumption for all sub-processes, from the total water consumption for the entire steel making process was calculated to be 2.89 liters per kg of steel produced (Margolis and Brindle 2000). This value can vary slightly depending on which processes are chosen and which assumptions are made. For this case, a continuous casting process was selected assuming the best technology available for the basic stock of semi-finished product. For plants with no waste water treatment on site or with outdated equipment, the water consumption rates can be higher. Although the water requirements, or water "used" are higher for each of the processes, much of the water is recycled or reused during the manufacturing process (Margolis and Brindle 2000).

Understanding how important water consumption is for the steel industry, and where in the various stages it is used, can lead to better decisions to reduce water input. The high water usage has already led to the closure of many coke ovens and smelters whose needs for cooling water and emissions of sulfur oxides resulted in significant environmental impacts (Ruth 2004).

To check the accuracy of the values, and to help ensure that the data was consistent, an additional data point was located for the water consumption of steel. According to a case study of BlueScope Steel's Port Kembla Steelworks, situated on a

760 hectare site approximately 80 km south of Sydney on the NSW south coast, by the end of 2004, through a series of capital improvements and recycling schemes water consumption was reduced to 2.6 liters per kg of steel produced (Hird 2006). This value is consistent for the previously determined value going through the entire steelmaking process. The Blue Scope environmental information posted on their website was also examined. They published an average of 2.0 liters per kilogram of steel produced as an average for the international operations. This value excluded recycled water. In other words, this international average for the operations is the value for water consumption (Blue Scope Steel 2010). Additionally, a Sustainability Report published by Nippon Steel, a Japanese steel producer was examined. Their water consumption value was 1.46 liter per kilogram, which included 90% percent recycling rate for water use (Nippon Steel 2010).

### 3.6.2 Aluminum

The data collected for water consumption for aluminum was also gathered from U.S. Department of Energy reports (Margolis and Sousa 1997; Margolis and Brindle 2000). Similarly to the production of steel, the report “Energy and Environmental Profile of the U.S. Aluminum Industry” described the entire aluminum making process from the raw materials to a semi-finished product. Although it mostly focused on energy consumption, it also explained typical water flow rates for the different steps along with recycling rates using the best available technology and acceptable discharges to meet EPA standards. Additional sources were used to help describe the process based on gaps from the report  (Margolis and Sousa 1997; Margolis and Brindle 2000).

The aluminum supply chain consists of a refinery, a smelter, and a casting plant (Tan and Khoo 2005). Initially, bauxite is extracted by mining (Schwarz 2004).The refinery accepts bauxite as raw material and converts it into alumina (Tan and Khoo 2005). It is converted to alumina via the Bayer process. According to the worldwide average, 2.3 tons of bauxite is necessary to produce 1 ton of alumina. Primary aluminum is produced via the Hall–He´roult process, a process of electrolytic reduction in a molten bath of natural and synthetic cryolite. The alumina is sent to a smelter to be processed into large-sized aluminum slabs (Tan and Khoo 2005). Two tons of alumina is necessary to produce 1 ton of primary aluminum as summarized in Table 9 (Schwarz 2004). Finally, the casting plant converts the slabs into small-sized billets. (Tan and Khoo 2005). The content of alloying ingredients is relatively high for cast aluminum. Cast aluminum cannot be reshaped plastically and must therefore be cast. In contrast, wrought aluminum can be reshaped plastically and its content of alloying ingredients is low. The alloys are converted to castings and semis. These are used for the production of final products (Schwarz 2004). Overall, this process, as shown in Figure 9, is very energy intensive, produces a significant amount of emissions, and requires a substantial amount of water. (Tan and Khoo 2005).

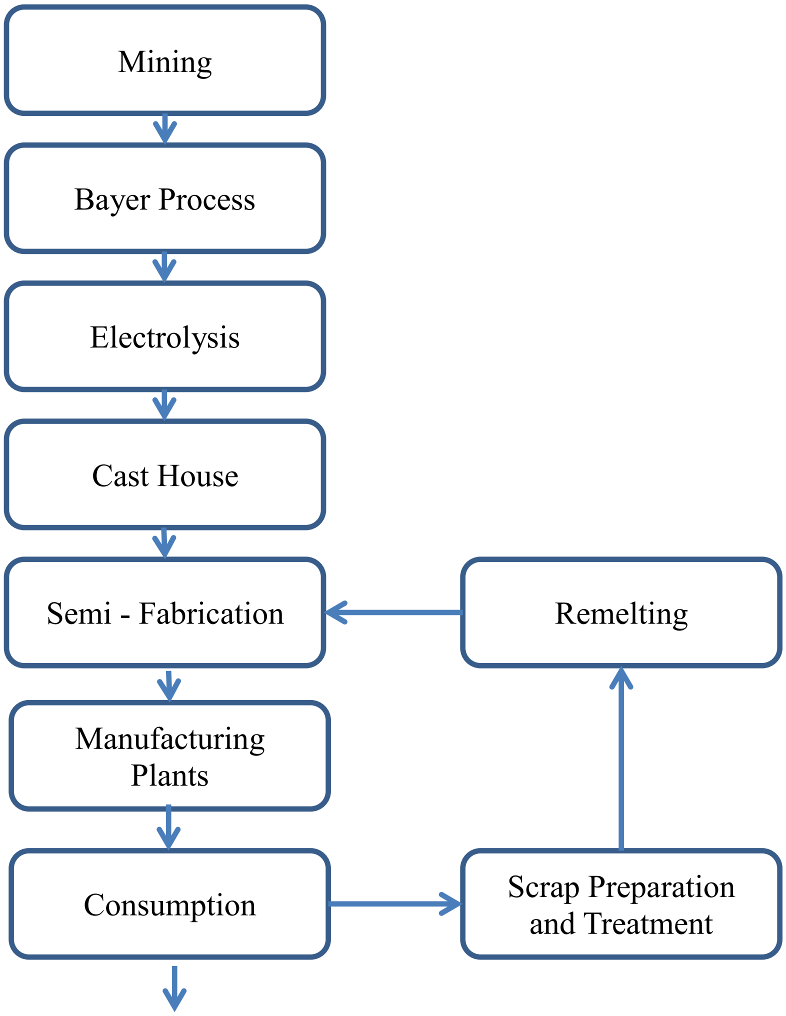

Figure 9: Aluminum Production Process (Schwarz 2004)

Table 9: Ratio of raw materials (Schwarz 2004)

| **Raw Material** | **Final Product** |
|---|---|
| 2.3 Bauxite | 1 ton of alumina |
| 2.0 tons of alumina | 1 ton of aluminum |

During the manufacturing of aluminum pieces for the automotive industry in production stage, water use is very important. After aluminum is injected into a pressure casting mold, water is used to circulate through a closed circuit and cool the mold. Water is also used to clean the mold after the casting process is complete, and to clean the machines that performed the operation. Although water is reuse in some form or another, the water consumption corresponds to losses in cooling the equipment, specifically the mold and machines, as evaporation (Sans, Ribo et al. 1998). Based on the information presented in the literature and summarized in APPENDIX B, the water consumption to make one kg of aluminum is 13.0 liters assuming an overall share of secondary aluminum is approximately be 32%, as shown in Table 10 (Margolis and Sousa 1997; Classen, Althaus et al. 2009). This total water consumption takes into account the differences in water consumption between using scrap and using new raw material. Basically, one multiplies the semi-fabrication water consumption by 0.68, which is the percentage of primary aluminum present in new cast aluminum, and the water consumption from scrap smelting/refining by 0.32, which is the percentage of secondary aluminum present in new cast aluminum.

Castings are the two last numbers for scrap smelting and semi-fabrication. Much of the water is used in the fabrication process due to high water requirements for casting. The more scrap metal that is used, the lower the water requirements. Just like steel, the water consumption during aluminum production can vary depending on which processes are chosen and on which assumptions are made during manufacturing. An effort was made to ensure that processes that were more typical and common were selected.

Table 10: Overview of aluminum production (Margolis and Sousa 1997)

| **Water Consumption Process** | **Water Consumed (Kg/Ton)** | **Water Consumed (Liters/Kg)** |
|---|---|---|
| Alumina | 4950.0 | 4.95 |
| Anode Production | 3215.0 | 3.22 |
| Aluminum production | 0.0 | 0.0 |
| Casting - Scrap Smelting | 320.0 | 0.32 |
| Casting - Semi-Fabrication | 10800.0 | 10.80 |

### 3.6.3 Copper

The water consumption for the production of copper was determined using a report from the Department of Interior titled “Energy and Environmental Profile of the U.S. mining industry.” (BCS Inc. 2002) Information was gathered from chapter 5, “Copper,” which outlined the entire process of production copper from ore. Although no direct numbers were given for the consumption of water, background data was given to infer this value by providing water uses and water recycling rates (BCS Inc. 2002).

According to (BCS Inc. 2002), the two major processes employed in the United States to recover copper from ores are either (1) pyrometallurgical methods (copper processing), or (2) hydrometallurgical methods (copper beneficiation). First, copper ore (which often contains less than one percent copper) is crushed and ground with water and placed in a concentrator. The rock/water slurry is subjected to physical and chemical processes inside a flotation tank. The chemical reagents assist the flotation process by acting as frothing and collector agents. As a result of the physical and chemical actions, the copper value rises to the surface of the flotation unit as froth. The material remaining on the bottom of the flotation tank (“gangue”) is partially dewatered and then discharged to tailing ponds for disposal. The concentrate resulting from the flotation circuit contains approximately 30 percent copper and, in some instances, may also contain significant recoverable concentrations of molybdenum. If molybdenum is readily recoverable, the concentrate is sent to the molybdenum plant for recovery; otherwise, the concentrate is ready for subsequent pyrometallurgical operations. Alternatively, the concentrate can be dewatered and the dry product may either be stored for further processing or shipped to another facility for processing. The collected water is usually recycled in the milling circuit. Copper processing processes employ high-temperature chemical reactions to extract copper from its ores and concentrates. Generally, these processes are used with copper sulfides and, in some cases, high-grade oxides. Depending on the copper mineral and the type of equipment, pyrometallurgical recovery may take as many as five steps:

roasting, smelting, converting, and fire refining. Copper beneficiation may consists of: crushing and grinding, washing, filtration, sorting and sizing, gravity concentration, flotation, roasting, autoclaving, chlorination, dump and in situ leaching, ion exchange, solvent extraction, electrowinning and precipitation (BCS Inc. 2002). A summary of the water consumption in copper production processes is given in Table 11 for a yearly production of 2, 493, 145, 2000 kg.

Table 11: Copper Yearly Water Consumption (BCS Inc. 2002)

| **Copper Process** | **$m^3$ / year** | **Liters / year** | **Liters / Kg** |
|---|---|---|---|
| Cooling water | 13,000 | 13,000,000 | 0.0005 |
| Process wastewaters | 4,891,000 | 4,891,000,000 | 0.1962 |
| Surface impoundment waste liquids | 615,000 | 615,000,000 | 0.0247 |
| Total | 5,519,000 | 5,519,000,000 | 0.2214 |

Used contact cooling water results from heat exchanging operations such as those taking place at the smelter. The water used for anode cooling is reported to contain dissolved arsenic, copper, and zinc and also to pick up aluminum and chlorides, probably from mold dressing compounds. Approximately 13,000 metric tons of contact cooling water is generated annually and is recycled and classified as spent material. Process wastewaters result from cooling and electrorefining operations. Process wastewaters may either be treated on site at wastewater treatment facilities they may be or discharged to tailings ponds, surface impoundments, or receiving streams. The waste exhibits the hazardous characteristics of toxicity (for arsenic, cadmium, lead, and mercury) and corrosivity. Approximately 4,891,000 metric tons of process wastewaters are generated annually and are recycled and classified as spent material. Surface impoundment waste liquids frequently contain mixtures of tailings and process wastewater (such as slag concentrate filtrate), which may have been treated in a wastewater treatment plant. Often, the solids are allowed to settle out and the liquids are discharged through permitted outfalls. Approximately 615,000 metric tons of surface impoundment liquids are generated annually and are partially recycled and classified as spent material. The water is measured for a production rate of 68,493 tons per day (BCS Inc. 2002). Assuming an annual production, the water consumption is then 0.22 liters of water per kg of copper.

### 3.6.4 Magnesium

Part of the data for magnesium was obtained from published work of a life cycle analysis for Magnesium (Gao, Nie et al. 2009). The study was published in The International Journal of Life Cycle Assessment. Actual values for water consumption were obtained from another life cycle analysis published in the "Journal of Cleaner Production" (Du, Han et al. 2010).

Magnesium (Mg) has a great potential to reduce vehicle weight, fuel consumption, and greenhouse gas emissions. Mg is considered as a very promising material that has potential to reduce vehicle weight. Other benefits of using Mg in automobiles can be its high shock and dent resistance and its greater ability to dampen noise and vibration better than aluminum. Mg production processes include Pidgeon, electrolytic, Carbothermic and solid oxygen-ion conducting membrane (SOM) process. Carbothermicand SOM processes have attracted attention because their lower production costs, but neither of the processes has yet been commercially developed. Less Mg is produced using electrolytic process than Pidgeon process due to its high production cost. Currently, the Pidgeon process dominates the production of Mg in the world (Du, Han et al. 2010).

The Pidgeon process was invented in early 1940's by Dr. Lloyd Montgomery Pidgeon of the Canadian National Research Council (NRC). This process is based on reducing the oxide of Mg by using silicon with a thermal energy reaction. The principal raw material is dolomite ore, which is calcined in rotary or vertical batch furnaces. The calcining process yields 'dolime' which is then ground and mixed in a specific ratio with finely ground ferrosilicon containing 75% of silicon. Calcium fluoride may be added to the mixture as a catalyst. The mixture is pelletized to make briquettes for reduction in the reduction furnace in which a vacuum is maintained. The Mg vapor emanating from the reaction zone condenses and form crowns on the tops of the retorts. The hot Mg crown is removed and taken for remolding, refining and casting into magnesium ingots (Du, Han et al. 2010). Eleven tons of dolomite ore are used to produce 1.0 ton of pure Mg at average in the Pidgeon Process surveyed. Ferrosilicon is another important material for Mg production using the Pidgeon process. Usually, 1.1 tons of ferrosilicon are used to produce 1.0 ton of Mg. The ferrosilicon is produced using iron oxide and silica as raw materials with an energy intensive electric arc furnace. In other steps, further electricity will be required, such as briquette production. (Du, Han et al. 2010).

Fresh water, used in small amounts in the process of magnesium production, is used as a cooling agent often with recirculation through a cooling tower. Waste water is subsequently discharged from the water treatment plant where suspended solids and oil/grease are monitored. The water consumption is 5 liters per kilogram of magnesium produced (Gao, Nie et al. 2009).

### 3.6.5 Zinc

Several sources were used to find the water consumption involve with Zinc production. One source, Pollution Prevention and Abatement Handbook by the World Bank Group, focused on describing the process of obtaining Zinc (World Bank Group 1998). The actual water consumption values were obtained from a paper, “LCA Case Study of zinc hydro and pyro-metallurgical process in China” published in The International Journal of Life Cycle Assessment (Xiao, Songwen et al. 2003). The paper provided a detailed description of where and how water was consumed.

Zinc can be produced pyrometallurgically or hydrometallurgically, depending on the type of ore used as a charge. In the pyrometallurgical process, ore concentrate is fed, in some cases after sintering, into a primary smelter. During sintering, a blast of hot air or oxygen is used to oxidize the sulfur present in the feed to sulfur dioxide. Blast furnaces are used in conventional processes for reduction and refining of lead compounds to produce lead. Modern direct smelting processes include QSL, Kivcet, AUSMELT, and TBRC. In the most common hydrometallurgical process for zinc manufacturing, the ore is leached with sulfuric acid to extract the zinc. These processes can operate at atmospheric pressure or as pressure leach circuits. Zinc is recovered from solution by electrowinning, a process similar to electrolytic refining. The process most commonly used for low-grade deposits is heap leaching. Imperial smelting is also used for zinc ores (World Bank Group 1998) .

Dust from raw material handling contains metals, mainly in sulfidic form, although chlorides, fluorides, and metals in other chemical forms may be present. Off-gases contain fine dust particles and volatile impurities such as arsenic, fluorine, and mercury.  Wastewaters are generated by wet air scrubbers and cooling water. Scrubber effluents may contain lead/zinc, arsenic, and other metals. In the electrolytic refining process, by-products such as gold and silver are collected as slimes and are subsequently recovered. Sources of wastewater include spent electrolytic baths, slimes recovery, spent acid from hydrometallurgy processes, cooling water, air scrubbers, wash downs, and storm water. Pollutants include dissolved and suspended solids, metals, and oil and grease (World Bank Group 1998) . The water consumption is 16.24 liters per kg of zinc. A breakdown of where water is consumed in the production of zinc can be found in Table 12.

Table 12: Water consumption for zinc processes (Xiao, Songwen et al. 2003)

| Process | Tons of water / Ton of Zinc | Liters/Kg |
|---|---|---|
| Roasting | 5.08 | 5.08 |
| Leaching | 1.00 | 1.00 |
| Electrolysis | 0.69 | 0.69 |
| Melting / Casting | 0.18 | 0.18 |
| Residue Handling | 2.82 | 2.82 |
| Auxiliary process | 6.48 | 6.48 |

### 3.6.5 Summary of Metals

Based on the information presented in the previous sections, a summary of the water consumption for the production of metals can as shown in Table 13. The most water intensive materials are Aluminum and Zinc. This is because both materials need more processing, which requires more water for cooling amongst other processes.

Table 13: Summary of Water Consumption for Production of Metals

| Material | Liters / Kg | Source |
|---|---|---|
| Steel | 2.89 | (Margolis and Brindle 2000) |
| Aluminum | 13.00 | (Margolis and Sousa 1997) |
| Copper | 0.22 | (BCS Inc. 2002) |
| Zinc | 16.44 | (Xiao, Songwen et al. 2003) |
| Magnesium | 5.00 | (Du, Han et al. 2010) |

### 3.6.6 Water Consumption of Aluminum Production vs. Steel Production

According to the research presented in this thesis, it appears that the production of aluminum significantly consumes more water than the production of steel. This can be seen by comparing the water requirements from Table 10 for aluminum and Table 8 for steel which is based on the information presented in APPENDIX B and APPENDIX A. The main driver behind this difference in water consumption is the result of higher evaporative losses of cooling associated with casting aluminum, for molds and machines, when compared to casting steel. Additionally, production of the raw materials required for aluminum processing also consume significantly more water.

The primary use of water in the cast house is for cooling of molten aluminum as it is formed in the casting process (Margolis and Sousa 1997) Water in aluminum casting is to circulate through a closed circuit and cool the mold. Water is also used to clean the mold after the casting process is complete, and to clean the machines that performed the operation. Although water is reused in some form or another, the water consumption corresponds to losses in cooling the equipment, specifically the mold and machines, as evaporation. The net water consumption for primary ingot casting is typically 10,800 Kg per metric ton of aluminum or 10.8 liters per kilogram. For secondary casting, the water consumption is 320 kg for metric ton or 0.32 liter per kilogram (Margolis and Sousa 1997).

On the other hand, steel requires less water during the casting operations. In continuous casting, the molten steel is solidified into a semi-finished shape for subsequent rolling in the finishing mill. Continuous casters usually include several separate closed-loop cooling water systems. Water use is categorized by function in the casting process: primary (mold), secondary (spray), and auxiliary (equipment). The primary cooling process is the non-contact cooling of the molten steel shell in the mold. Closed-loop, non-evaporative cooling is primarily employed when high surface and strand quality are required. Secondary or spray cooling occurs as the strand exits the mold, with contact water sprays covering the surface of the strand. Auxiliary cooling is non-contact or internal cooling of the casting equipment. Direct contact water systems are used for spray cooling. Applied water rates for the contact systems are typically about 3,600 gallons per ton of cast product. As with other contact systems, this system will typically utilize evaporative tower systems for cooling. For continuous casting, the BPT limitations assume closed loop cooling for the casting machine and a mold cooling water system and recycle 98% for spray water resulting in a water consumption of 72 gallons per ton or 0.27 liters per kilogram (Margolis and Brindle 2000).

It does appears that using recycled aluminum can have a significantly effect on of the overall water consumption of casting aluminum. But even if were to take use more recycling into account, the processing of aluminum still consumes more water because of alumina production and anode production. (Schwarz 2004). Alumina is produced with the Bayer process, which requires a considerable amount of process water for washing and filtering. Typical process water consumption 4590 kg for metric ton of alumina or 4.95 liters per kilogram (Margolis and Sousa 1997). Additionally, water is required to produce anodes, used in the electrolysis of aluminum oxide to form aluminum. The production of anode net water consumption of water is 3,215 kg of water per metric ton of anode or 3.22 liters per kilogram, mostly in the wet plant wet air pollution control and to cool green anode blocks to prevent them deforming (Margolis and Sousa 1997). In other words, even if the best case scenario were to be used for aluminum casting, producing this material would still significantly consume much water because of the production of alumina and anode.

On the other hand, the only raw material required for iron or steel production besides iron ore are coke and sinter, which do not consumed much water when compared to alumina and anode production. The largest volume of water used in coke plants is for non-contact cooling in a variety of cooling and condensing operations with a process flow of up to 900 gallons per ton (Ellis, Dillich et al. 2000; Margolis and Brindle 2000). Although the best technology can recycle final cooler water, consumption of water for the coke quenching can still be 120 gallons per ton of coke. The typical volume of process wastewaters generated at a well-controlled coke plant is approximately 100 gallons per ton of coke produced (Margolis and Brindle 2000). So, the total water consumed is 220 gallons per ton or 0.83 liters per kilogram. The main uses of water in a sintering plant are for controlling the moisture content of the pre-sinter mix, for dust control, and for sinter produce cooling. Wastewaters, typically 120 gallons per ton of sinter, are generated from the wet air pollution control devices on the windbox and discharge ends of the sinter machines.

In summary, the production of aluminum consumes more water because of higher evaporative losses. Additionally, the production of aluminum requires other raw materials, which also consume significant amounts of water when compared to material input requirements to produce steel. These results are consistent with the water consumption values from Alcoa, which reports a consumption of 7.8 liters per kilogram, when compared to the values from Nippon Steel, which reports a water consumption value of 1.46 liters per kilogram (Alcoa 2007; Nippon Steel 2010). Both appear to be making efforts to recycle water and explicitly mention that this water consumption values are typically associated with evaporative losses of their cooling operations.

## 3.7 Production of Nonmetals

### 3.7.1 Rubber

Two main sources were used to determine the water consumption for rubber, as in a car tire, for the supply chain. Both were life cycle analyses done by companies and are publicly available. One was prepared by Continental, and the other by Bridgestone. The Continental LCA described on how waster could be used but did not explicitly contained information on the definition of water consumption (Krömer, Kreipe et al. 1999). The Bridgestone publication actually quantifies that company's overall water consumption to produce tires (Bridgestone 2010).

The feedstock for tires is manufactured from fossil, mineral and replenishable resources. On the basis of its physical and chemical properties, this feedstock subsequently provides the performance potential for the functioning tire. The structural parts are manufactured from the feedstock and assembled to form the green tire, which is then vulcanized to yield the functioning tire (Krömer, Kreipe et al. 1999).

The water consumption is the supply chain for rubber tires is made up of cooling water and process water. Cooling water is usually fed into circuits and can thus be used over a long period of time. It exhibits a low negative impact factor. Process water is directly involved in the manufacturing processes and is disposed of as waste water. The largest water use is required for the acquisition of raw materials for the tire. The water consumption in conjunction with the acquisition of raw materials for the carbon black/rayon tires under consideration here is as follows: the manufacture of synthetic rubber (SBR), to obtain rayon, for the manufacture of natural rubber, and for the manufacture of chemicals (Krömer, Kreipe et al. 1999). The water consumption rate is 6 m^3 per ton or 6 liters per kilogram. Much of the water is used during tire production is used during cooling. Raw materials acquisition for a car tire is characterized by a high water requirement. The use of cooling water poses less of a problem from an ecological viewpoint as the negative impact. It should be noted that retreading of tires consumes less than 3 percent of the water that is consumed in the production of new tires (Krömer, Kreipe et al. 1999).

### 3.7.2 Plastics

Similarly to the issues seen while locating data on water consumption for other materials, locating data for plastics resulted in a wide range of numbers that did not always specifically define their scope. Finally, a publicly available document prepared for The Plastics Division of the American Chemistry Council gave a definition consistent with the scope of this thesis and provided water consumption numbers (Franklin Associates 2010). Information for some of the other plastics not mentioned in the report was located from a variety of sources that sometimes provided a description of the processes or a water consumption number based on comparable metrics.

#### 3.7.2.1 Polyurethane

MDI (methylene diphenyl diisocyanate) and TDI (toluene diisocyanate) are high tonnage products, which comprise about 90% of the total diisocyanate market. The predominant use of MDI and TDI is in the manufacture of polyurethanes. MDI and TDI are used almost entirely for the production of polyurethane polymers. Polyurethanes are produced by reacting diisocyanates with polyols and other chemicals.

Water, a reactive agent, causes blowing by reacting with MDI or TDI to form carbon dioxide gas within the polyurethane reaction mixture. According to the type of blowing agent and the concentration in the reacting mix, it is possible to produce polyurethane polymers of different densities, and of different thicknesses of skin. Water and other blowing agents are used together in formulations to achieve the required balance of density and physical properties.

The average water consumption in the polyurethane industry was prepared using average data, with boundary limits starting at the extraction from the earth and terminating at the factory gate, to ensure that the information was representative of the industry as a whole. The value show that the water consumption is small (Szycher 1999). Table 14 shows typical input data for a hypothetical flexible foam producing operation based on information presented in APPENDIX C. The column on the left shows the material input into the process while the column on the right shows the material production rate, i.e. how much of the material is consumed making a kg of polyurethane foam.

Table 14: Production factors for polyurethane foam (Boustead 2005)

| Material Input | Material production rate per Kg |
|---|---|
| Water | 0.021 |
| TDI | 0.285 |
| Polyol | 0.713 |

#### 3.7.2.2 Other Plastics

Data consumption in the making of plastics and plastic products was inconsistent and varied significantly depending on which assumptions were made by the manufacturers. One study conducted by outside consultants, Franking Associates, for the plastics division of the American Chemistry Council, provided a definition of water consumption that was consistent with the set definition in this paper (Franklin Associates 2010). In their analysis, water consumption was defined as water consumed in the process (e.g. water that becomes part of the product or evaporation loss), and water removed from one water source and released to a different receiving body of water. Cooling water that is circulated in a closed-loop system is not included. Although their analysis provided data for the making of the plastics, there was a lack of data for the raw materials and intermediate chemicals for some of these processes. Again, rather than providing very specific numbers, the analysis showed a trend that is consistent with the set boundaries of the analysis. Their data, Table 15, helps to illustrate typical values for water consumption in the making of the plastics and how they differ for each plastic (Franklin Associates 2010).

Table 15: Water consumption for plastics (Franklin Associates 2010)

| Material | Water Consumption (Liters/Kg) |
|---|---|
| High Density Polyethylene (HDPE) Resin | 1.49 |
| Low Density Polyethylene (LDPE) Resin | 4.16 |
| Production of PROPYLENE | 1.78 |
| Production of Polyvinyl Chloride (PVC) Resin | 1.01 |
| Production of Acrylonitrile -Butadiene -Styrene (ABS) | 2.60 |
| Production of Polyether Polyol for Rigid Foam | 0.04 |
| Polyether Polyol for Flexible Foam Polyurethanes | 0.45 |
| Production of Pure and Polymeric MDI | 1.33 |

Other materials that are important because of their amount as part of the material composition are polyester, nylon. One source listed that there is approximately 17 l/kg of water consumption in polyester fiber production (M.Kalliala and Nousiainen 1999).

#### 3.7.2.3 Glass

An article, “Application of life cycle assessment to the production of man-made crystal glass,” in The International Journal of Life Cycle Assessment contained a detailed description of the glass making process and included information on the related water consumption. Other information was included from various resources to help explain the process (Pulselli, Ridolfi et al. 2009).

The most common furnace used for producing glass melt is the continuous regenerative type, with either the side or the end ports connecting brick checkers to the inside of the melter. Checkers conserve fuel by acting as heat exchangers; the fuel combustion products heat incoming combustion air. The molten glass is refined (heat conditioning) and is then pressed, blown, drawn, rolled, or floated, depending on the final product. Damaged and broken product (cullet) is returned to the process (World Bank Group 1998).

Water in the glass making process is consumed during two stages: cutting, and polishing. Cutting activities can give rise to dust emissions, which are controlled by cutting under liquid. Polishing uses water to wash material. A summary of the water consumption for the production of glass can be found in Table 16 (Pulselli, Ridolfi et al. 2009).

Table 16: Glass manufacturing (Pulselli, Ridolfi et al. 2009)

| Process | Water Consumed (Liters/Kg) |
|---|---|
| Cutting | 1.03 |
| Polishing | 2.57 |

### 3.6.3 Summary of Nonmetals

Based on the information presented in the previous sections, a summary of the water consumption for the production of metals can as shown in Table 17. As can be seen, compared to the production of metals, nonmetals mostly consume minimal amount of water.

Table 17: Summary of Water Consumption for Production of Nonmetals

| Materials | Water Consumption (Liters/Kg) | Source |
|---|---|---|
| Rubber | 6.00 | (Bridgestone 2010) |
| Glass | 3.60 | (Pulselli, Ridolfi et al. 2009) |
| ABS | 2.60 | (Franklin Associates 2010) |
| Polyester | 17.00 | (M.Kalliala and Nousiainen 1999) |
| Polyethylene | 4.16 | (Franklin Associates 2010) |
| Polypropylene | 1.78 | (Franklin Associates 2010) |
| Polyurethane | 0.72 | (Boustead 2005) |
| Polyvinyl chloride | 1.01 | (Franklin Associates 2010) |

## 3.8 Comparison of Water Data

By comparing the information from EcoInvent in Table 7 with the data from Table 17, a significant difference in numbers can be seen between the two values as shown in Table 18. This huge difference has to do mainly with the fact that the data from EcoInvent is limited as a basis for water since it does not necessarily include important factors like recycling of water or evaporation. In essence, the EcoInvent data does not distinguish between water that goes to the sewer system (and can thus be reused) versus water that is truly lost (consumed) due to evaporation or encapsulation in a material.

Table 18: Comparison of Water Data from EcoInvent and Literature Sources

| Material | EcoInvent (Liters/Kg) | Literature Sources (Liters/Kg) |
|---|---|---|
| Steel (Raw Material) | 31 | |
| Steel (Processing) | 55 | |
| Total Steel | 86 | 2.89 |
| Aluminum (Raw Material) | 106 | |
| Aluminum (Processing) | 97 | |
| Total Aluminum | 203 | 13.00 |
| Copper (Raw Material) | 198 | |
| Copper (Processing) | 66 | |
| Total Copper | 264 | 0.22 |
| Zinc (Raw Material) | 40 | 16.44 |
| Rubber (Processing) | 120 | 6.00 |
| Glass | 14 | 3.60 |
| ABS | 178 | 2.60 |
| Nylon | 186 | |
| Polyester | 248 | 17.00 |
| Polyethylene | 32 | 4.16 |
| Polypropylene | 43 | 1.78 |
| Polyurethane | 380 | 0.72 |
| Polyvinyl chloride | 609 | 1.01 |
| Magnesium | 475 | 5.00 |

### 3.9 Water Analysis per Literature Data

Multiplying water consumption values from the summary and Table 17 with the car material composition presented can be used to determine the total water consumption for the production of materials. Some of the materials that were originally omitted because no data was found were still added for completeness. The result shows that 5,570 liters of water are consumed in this process. As can be seen from Table 19 and Figure 10, most of the water consumption in a vehicle goes into producing steel, aluminum, and rubber. Although aluminum is second in terms of material in a typical U.S. vehicle, its water consumption as part of the supply chain is nearly as high as that of steel. This number can greatly be reduced if more recycled aluminum is used as described in earlier sections.

An effort was made to ensure that the information found included recycling of water in all processes and to explicitly explain what was meant by water consumption and to ensure that this water consumption definition was consistent with that set out in the scope. However, is inevitable that some discrepancies in the data could exist. More importantly, the analysis shows a trend in water consumption and explains in detailed where most of the water is used, specifically in the metals as they tend to be the greater consumers of water in the supply chain. These values can vary depending on the vehicle, model, and even for manufacturing centers depending on individual processes and technologies being implemented.

Table 19: Water consumption for Vehicle Material Production

| Material | Water Consumption (liters/kg) | Vehicle Mass (kg) | Vehicle Water Consumption (liters) |
|---|---|---|---|
| Steel | 2.89 | 793.8 | 2294.1 |
| Aluminum | 13.00 | 154.2 | 2004.9 |
| Copper | 0.22 | 20.4 | 4.5 |
| Zinc | 16.44 | 7.3 | 119.4 |
| Rubber | 6.00 | 60.3 | 362 |
| Glass | 3.60 | 39.9 | 143.7 |
| ABS | 2.60 | 24.9 | 64.9 |
| Nylon | -- | 11.3 | |
| Polyester | 17.00 | 12.2 | 208.2 |
| Polyethylene | 4.16 | 16.3 | 67.9 |
| Polypropylene | 1.78 | 21.3 | 38 |
| Polyurethane | 0.72 | 44.0 | 31.7 |
| Polyvinyl chloride | 1.01 | 12.7 | 12.8 |
| Other metals (Magnesium) | 5.00 | 43.5 | 217.7 |
| **Total** | | **1262.4** | **5569.6** |

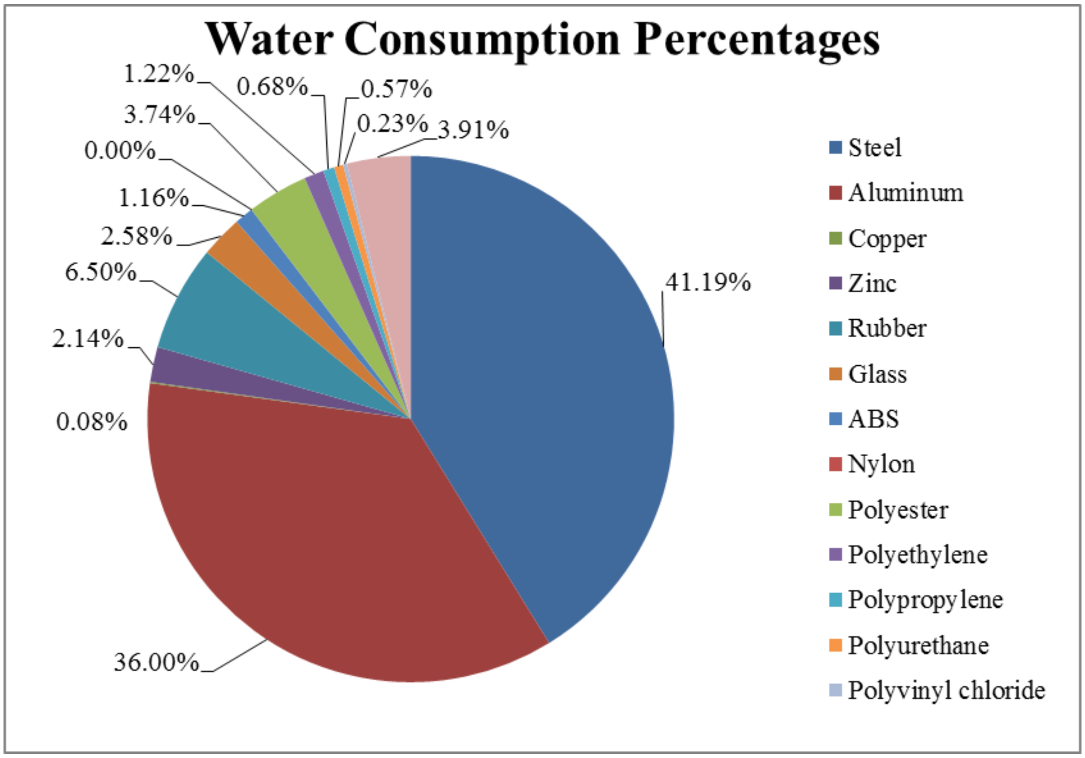

Figure 10: Water Consumption Percentage

### 3.10 Water Analysis per EcoInvent Database

A comparison was made with water data for materials found in the EcoInvent Database as shown in Table 20 . The information was used to determine how much water went into the production of the materials and semi-finished parts. The data found only showed the amount of water that went into a system, without taking into account recycling rates or reuses of water, and without breaking down any steps. EcoInvent reports often mentioned that recycled water was not accounted for in the inventory. Basically, no definition or actual explanation could be found regarding water use or water definition on the EcoInvent reports. The data from the EcoInvent Database can be found in Table 20 (Classen, Althaus et al. 2009). Regardless of how the model is set up in terms of the material composition and assumptions made for the various manufacturing processes in the data, the numbers in the EcoInvent data base for water are significantly higher further indicating that their data pertains to water use.

Table 20: Water Analysis based on EcoInvent Data (Hischier 2007; Classen, Althaus et al. 2009)

| Material | Water Consumption (liters/kg) | Vehicle Mass (kg) | Vehicle Water Consumption (liters) |
|---|---|---|---|
| Steel (Raw Material) | 31 | | |
| Steel (Production) | 55 | | |
| Total | 86 | 793.8 | 68,266 |
| Aluminum (Raw Material) | 106 | | |
| Aluminum (Production) | 97 | | |
| Total | 203 | 154.2 | 31,307 |
| Copper (Raw Material) | 198 | | |
| Copper (Production) | 66 | | |
| Total | 264 | 20.4 | 5,388 |
| Zinc (Raw Material) | 40 | 7.3 | 290 |
| Rubber (Production) | 120 | 60.3 | 7,240 |
| Glass | 14 | 39.9 | 559 |
| ABS | 178 | 24.9 | 4,441 |
| Nylon | 186 | 11.3 | 2,109 |
| Polyester | 248 | 12.2 | 3,037 |
| Polyethylene | 32 | 16.3 | 523 |
| Polypropylene | 43 | 21.3 | 917 |
| Polyurethane | 380 | 44.0 | 16,719 |
| Polyvinyl chloride | 609 | 12.7 | 7,735 |
| Other metals (Magnesium) | 475 | 43.5 | 20,682 |
| **Total** | | **1262.4** | **169,212** |

Although the percentages differ, compiling the data from the EcoInvent database as shown in Figure 11 indicates a similar trend to water consumption calculated using the literature data. For instance, the water use and water consumption is still highest for steel, as comprises the largest mass of a vehicle. Aluminum is still second but glass moves up to third in water use. Regardless of how the model is set up in terms of the material composition and assumptions made for the various manufacturing processes in the data, the numbers in the EcoInvent data base for water are significantly higher, namely, 30 times higher. This huge discrepancy seems to come from the fact that the LCA databases account for water use and not just water consumption. Water consumption due to evaporative losses is typically a fraction of water use.

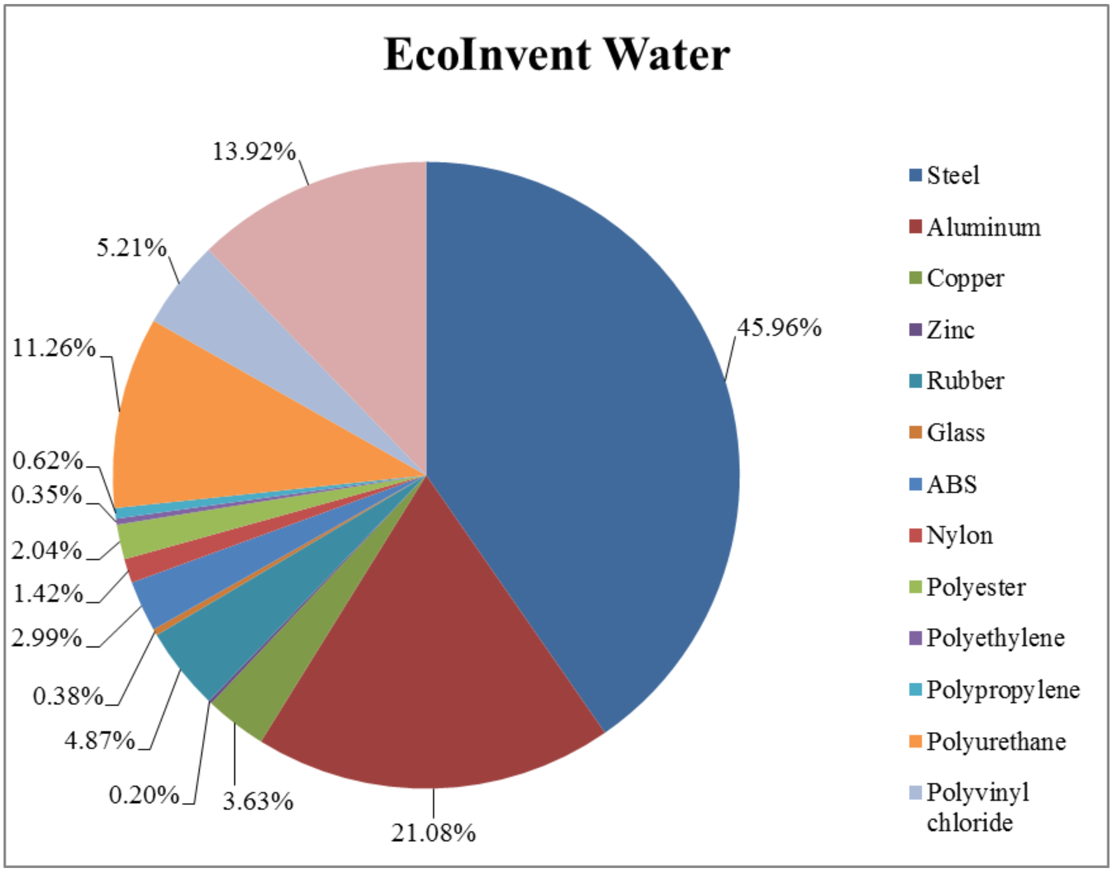

Figure 11: Water Analysis using EcoInvent data

However, if were to compare the water inputs, not just the water consumption, into considerations from the literature sources, we would see a similar magnitude to that from EcoInvent. In other words, if we were trying to simply measure the water inputs, EcoInvent would be a valid source for the material production phase for the life of a vehicle.

## 3.11 Material Production Water Comparison

By comparing Table 19 with Table 20, a significant difference in the values can be found as shown in Table 21. The EcoInvent data base numbers are much higher by comparison as the percentage difference shows. Recycling of water can greatly reduce the water consumption. What this comparison illustrates is that, although the database show similar trends, the numbers in EcoInvent for water are much (30x) higher.

Table 21: Water Consumption Comparison

| Material | EcoInvent Data (liters) | Literature Data (liters) | Difference (liters) |
|---|---|---|---|
| Steel | 68,265.9 | 2,294.1 | 65,971.9 |
| Aluminum | 31,306.7 | 2,004.9 | 29,301.8 |
| Copper | 5,388.2 | 4.5 | 5,383.8 |
| Zinc (Raw Material) | 290.4 | 119.3 | 171.1 |
| Rubber (Production) | 7,239.6 | 362.0 | 6,877.6 |
| Glass | 558.9 | 143.7 | 415.2 |
| ABS | 4,440.7 | 64.9 | 4,375.9 |
| Polyester | 3,037.2 | 208.2 | 2,829.1 |
| Polyethylene | 522.5 | 67.9 | 454.6 |
| Polypropylene | 916.7 | 38.0 | 878.8 |
| Polyurethane | 16,719.2 | 31.7 | 16,687.6 |
| Polyvinyl chloride | 7,734.9 | 12.8 | 7,722.1 |
| Others Metals | 20,681.5 | 217.7 | 20,463.8 |
| **Total** | **169,211.85** | **5,569.60** | **161,533.0** |

## 3.12 Conclusion

This chapter focuses on assessing the amount of water consumed in the production of raw and semi-finished materials for a mid-sized gasoline powered US vehicle. According to my analysis, 5,570 liters of water are consumed for the extraction and processing of materials to produce a typical US vehicle Even though the production can require significant amounts of water, with the use of the best available technology, much of it can be recycled and reused in the form of cooling water or recycled waste water. The 5,570 liters is less than the approximately 10,000 liters reported in (Schweimer and Levin 2000) for the smaller Golf vehicles' material production, but is directionally in the same order of magnitude.

Using water data found in the EcoInvent V2.2 database resulted in 169,212 liters of water for producing the materials for the same car. The comparison also showed that the water numbers in the database were significantly (30 times) higher than those found in government documents, in published papers, and in publicly available company information. The EcoInvent supporting information did not provide any background information regarding what assumptions or definitions were given for the water numbers. This important trend will serve as a basis in future chapters to initially quantify water use from EcoInvent and then to continue through to determine water consumption based on literature review.

A directional trend and areas of concern of the water consumption in the supply chain for the automobile industry can be observed, however. As it was shown, most of the water was consumed in the production of steel, aluminum and rubber, even when taking into account the water recycling rate. Given the importance of steel as part of the water consumption footprint of the automobile supply chain, more detailed descriptions were given for this process. Although one source gave specific values for the water consumption in the steel making process, several others were used to confirm where water was consumed.

Some options exist for reducing the water footprint of a car's raw materials. The research showed most of the water was consumed for cooling and cleaning. The most obvious, but potentially costly, solution to helping ensure that less water is consumed in the various manufacturing processes is by the introduction of some kind of onsite waste water recycling plant, or by reusing the water a number of times before disposal. Other solutions could simply mean upgrading the equipment to make sure that the best available technology is being utilized or reorganizing the flow of water within any given set of processes to help cool or clean as efficiently as possible. Depending on the resources available, and on the actual part of the supply chain, the solutions will vary.

Most of the data presented in the chapter illustrates the use of the best available technology by U.S. standards. Most of the information found was based on the U.S. industry which must meet certain EPA environmental regulations so the use of wastewater recycling seemed a common trend. This trend may not exist in other localities such as low cost countries, however, where many automotive suppliers reside. This may mean that the actual water “splash” from materials production may be higher than stated in this paper.

# CHAPTER 4:

# PARTS PRODUCTION

## 4.1 Scope and Methodology

An automobile is a very complex system of assemblies, all connected together for the purpose of transporting the users from one location to the next, each of which is generally composed of a number of constituent materials. Examining every part to determine water consumption, starting with specific materials, to manufacturing processes, to transportation and individual assemblies would take a great deal of resources, not to mention specific, sometimes propertiery information, from auto makers, and cooperation from many vendors. These vendors may not even record their water use, let alone their water consumption, so contacting them, or finding more about their company enviromental policies may not help to quantify water consumption for the production of parts.

Complicating the process of tallying up the various burdens for the production of parts in a vehicle is the fact that some are manufactured by the major automobile companies and others outsourced to suppliers tier 1, tier 2, etc. An assembly made by a Tier 1 supplier and purchased by an auto manufacturer likely contains components made by Tier 2 suppliers. For example, a dashboard assembly produced by a Tier 1 supplier includes a speedometer made by a Tier 2, which in turn contains subcomponents made by other suppliers. In addition, the burdens incurred in the production of any product at a facility are often difficult to attribute or allocate to that particular product, as more than one product is commonly made there. Finally, these burdens include both fixed and variable components, which likely vary from one manufacturer to another. Hence, it is clear that tracing the water consumption burdens through a maze of automaker and Tier 1 and 2 operations is at best an onerous task, the result of which is sure to contain considerable uncertainty (Sullivan, Burnham et al. 2010).

Instead of going through each indivudal component in a vehicle, which can have upwards of 10,000 unique parts, the most efficient course of action is to identify major manufacturing processes associated with a typical material composition of a vehicle and to couple them with the main material outputs associated with the production of components and assemblies (Veloso and Kumar 2002).

For this analysis, water consumption was only determined for the processes themselves without taking into account logistics, water from energy consumption, and the construction of infrastructure. The reasoning behind this limitation in scope is that the data for these aspects, with perhaps the exception of energy, is limited and could include resources consumed in the manufacturing of items other than automobile components that are of interest here. Including water consumption for the production of energy at this point would be inconsistent with the rest of the research at this stage and would widen the scope to the point where it would become unmanageable for this analysis.

## 4.2 Data Sources

Several sources were used to gather the necessary information to develop the water consumption assessment in the manufacturing of automobile parts. The sources provided a wide range of perspectives but were mostly based on recorded data from manufacturing centers and reference materials based on real world applications. Although no individual sources are referenced in this section, due to the large number for each category, the three main types are explained below.

First, environmental reports of companies in the business of manufacturing automobile components, whenever available, were analyzed to calculate average inventories of machine operations, factory operations, and factory infrastructure. It should be noted that companies publishing environmental reports have a certain environmental awareness and probably have an environmental impact below average. This means that even if a worst case scenario is assumed for companies publishing their environmental reports, their natural resource consumption may still not fully represent their respective industries but rather be below the typical expected values.

Secondly, published documents, whether from books or articles in journals, as well as online sources, were used to provide additional data whenever the environmental reports were lacking. To check the validity of the information, more than one source was often used for important numbers whenever possible. The sources were selected if the information presented was believed to have a basis in the form of field data or was obtained from reputable industry organizations.

Finally, the EcoInvent database was used to provide water inputs into the various processes. These numbers typically represented the input to the system, without necessarily recycling or reusing water. Although in some instances the water vapor was defined, the scope did not fully explain the boundaries of the analysis.

## 4.3 Uncertainty

There is a broad range of efficiency and natural resources consumption depending not only on the type of equipment but also on different practices associated with the manufacturing processes. For example, energy consumption of a machine during set up and waiting is significantly higher in the case of small series compared to mass production (Steiner and Frischknecht 2007). Furthermore, whenever the information on resources consumption is published for a company, research has shown that within a short period, significant reductions in the environmental impact of the production are feasible as soon as a certain environmental awareness arises in a company, as demonstrated by a decision to publish an environmental or sustainability report (Steiner and Frischknecht 2007). Finally, assumptions were made that tended to align with the worst case scenario for the recycling of water. If a facility does not recycle water in anyway, or has the best technology to maintain low levels of water consumption, their values may differ. Rather than providing a specific number for water consumption, what this analysis does is to provide a range and magnitude for expected values for the different processes. Because few life cycle studies have been conducted in the automobile manufacturing area focusing on water, this thesis cannot reliably report average and standard deviation results for the processes listed, although an effort was made to compare different sources whenever possible to help validate the magnitude of water consumption associated with a specific process (Sullivan, Burnham et al. 2010).

## 4.4 Literature Review

Berry and Fels in 1972 were among the first to calculate natural resource consumption in the manufacturing of a vehicle. Their approach uses financial, material, and energy data from the Census of Manufacturers. Unfortunately, their approach using these data is neither well documented nor (by their own admission) straightforward (Sullivan, Burnham et al. 2010). Other studies like Kobayashi in 1997 itemized the components of a vehicle life-cycle inventory to identify key processes, including stamping, casting, welding, heat treatment, forging, painting, molding, machining, plating, and body and part assembly. However, like most studies, it focused on energy consumption (Kobayashi 1997).

A more recent study by the Argonne National Laboratory conducted detailed descriptions of material flow rate, including percentages coupled with different processes (Sullivan, Burnham et al. 2010). The authors used information from the United States Council for Automotive Research Generic Vehicle Life Cycle Inventory Study. Although the report focused on energy consumption and emissions, their processes and evaluations for the manufacturing stages have a methodology similar to that used in determining the water consumption footprint. No single report could be found that focused on water consumption in the manufacturing stage of a vehicle. Rather, all of the information located had individual processes in which water input, or water consumption, was only a small part of the environmental analysis (Sullivan, Burnham et al. 2010).

### 4.5 Material Composition

Because of the way materials are handled during auto manufacturing and because of my methodology for determining the water consumption, a simpler material composition model can be used based on the comprehensive one presented in Table 2. The ferrous materials will be placed into either the category of cast iron or steel. The plastics will also be combined into one category. Finally, the liquids and other materials are removed. Table 22 shows the material composition that will be used to calculate the water consumption.

Table 22: Simplified Material Composition Model (Das, Curlee et al. 1995)

| Material | Weight (Kg) |
|---|---|
| Iron | 194.82 |
| Steel | 598.97 |
| Aluminum | 154.22 |
| Copper | 20.41 |
| Other Metals | 7.26 |
| Glass | 39.92 |
| Plastics & Textiles | 181.44 |
| Rubber | 60.33 |

### 4.6 Process Overview: Metal Components

The making of most standard automobile parts typically involves a number of similar processes that are adjusted for each case to yield different products. For metal components, encompassing anywhere from 70 %-85 % of a vehicle by weight, parts manufacturing may involve many categories, each having its subset of individual processes for which water can be used and consumed (Das, Curlee et al. 1995). However, they can be summarized into major sets encompassing most of the intermediate categories as shown in Figure 12. These percentages of material flows for the various manufacturing stages were based on a report from the Argonne National Laboratory (Sullivan, Burnham et al. 2010). The processes will be analyzed for each metal to determine the water consumption. The material composition for metals will then be coupled with the water consumption for each process. For some of the metal components, more than one major process will be applied in manufacturing the final product. For instance, an aluminum part may be cast, and then machined, so water consumption for both processes must be included in the analysis.

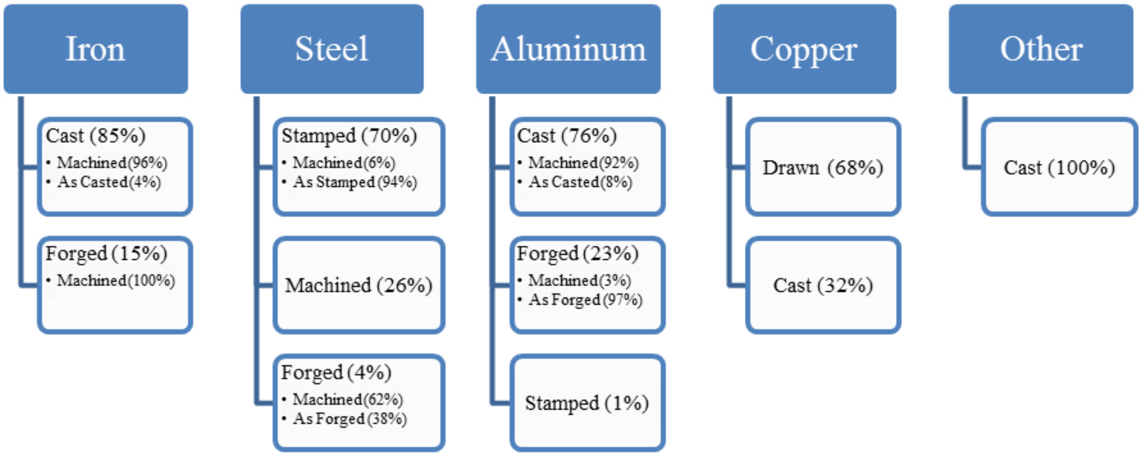

Figure 12: Manufacturing Processes for Metal Parts (Sullivan, Burnham et al. 2010)

To further check the percentage of material undergoing each process, additional data points were found, as shown in Table 23. The information presented is based on a study of the greenhouse emissions related to aluminum; the study broke down the major components and manufacturing process of aluminum for various cars (Bertram, Buxmann et al. 2009). What can be seen from the table below is that most of the weight of the aluminum pieces, 84% can be attributed to casting. It can also be seen that 25 % percent of the vehicle is forged. Both values are similar in magnitude to those seen in Figure 12. The difference is that the table has more parts seeing more than one process, such as casting and then forging, as opposed to just being forged. This description of aluminum manufacturing helps to further validate the assumptions for the major processes involved in manufacturing of vehicle parts

Table 23: Aluminum components (Bertram, Buxmann et al. 2009)

| Component | Manufacturing Process | Mass (kg) |
|---|---|---|
| Engines | Casting | 51.6 |
| Transmission and drive line | Casting | 31.5 |
| Chassis suspension and steering | Casting / Forging / Extrusion / Sheets | 10.1 |
| Wheels and Spares | Casting / Forging / Sheets | 23.6 |
| Heat Exchangers | Sheets / Extrusions | 14.5 |
| Brakes | Casting / Forgings | 3.5 |
| Closures | Sheets / Extrusion | 2.5 |
| Body and IP Beams | Sheets / Extrusion / Casting | 0.5 |
| Heat Shields | Sheets / Extrusions | 1.8 |
| Bumper Beams | Extrusion | 0.8 |
| All others | Extrusion / Castings | 4.1 |
| **Total** | | **144.5** |

### 4.7 Process Overview: Nonmetal Components

Similar to the metal components, the components encompassing the rest of the vehicle, consisting mainly of plastic, rubber, and glass components, can be categorized into a few major manufacturing processes as shown in Figure 13. These percentages of material flows for the various manufacturing stages were also based on a report from the Argonne National Laboratory (Sullivan, Burnham et al. 2010). Water consumption for each manufacturing process will be coupled with the material input. Unlike metals, the nonmetal parts typically do not have a major secondary process during manufacturing so one manufacturing process can be assigned to a percentage of the material for each category.

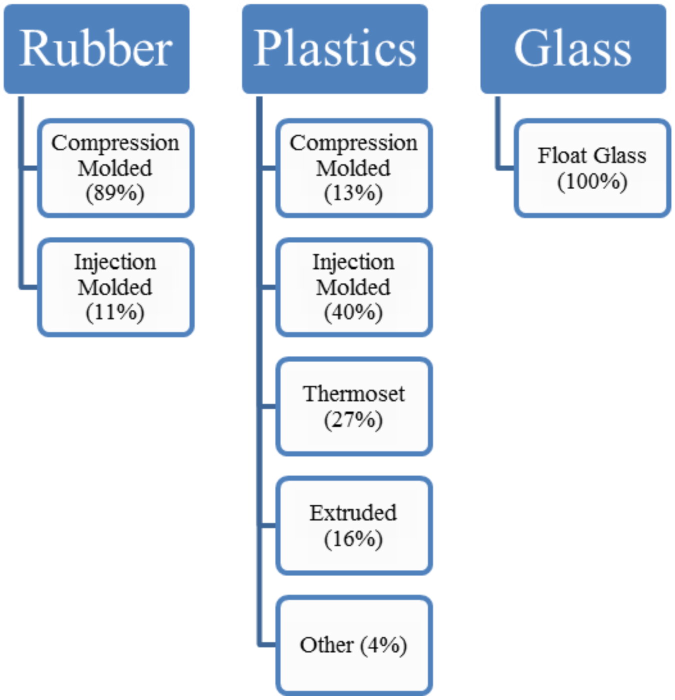

Figure 13: Manufacturing Processes for Nonmetal Parts (Sullivan, Burnham et al. 2010)

### 4.8 Uses of Water in Manufacturing

The main uses of water in manufacturing are in cooling, processing, and cleaning. This generalization seems to extend across most manufacturing processes for both metals and nonmetals. Water use in cleaning rarely consumes water, even if it does create wastewater and has an impact on the environment, according to the definition set forth at the beginning of the paper, so it will be neglected for most analysis cases. Water use in processing involves treating material after the initial process, say for quenching metals or initiating a chemical reaction in plastics. Water for cooling draws heat and energy away from not just materials but also from the machinery used to process these materials. Depending on the set up of a system, whether it is an open loop system or a closed-loop system, both water use and water consumption are highest for cooling. The hotter the part or equipment gets, the more water is use to dissipate the heat, and the more water that is consumed. As will be described in some of the future sections, water consumption in manufacturing is most commonly associated with cooling.

## 4.9 Water Use per EcoInvent Data

Before compiling any data for water consumption, an initial assessment was completed using data from EcoInvent. The scope of the information presented in their reports was limited at best and varied for each of the process. A summary of the water input values based on the database can be found below in Table 24. The results of the water use, as a percentage, can be found below in Figure 14. The data points to the manufacturing processes for steel, iron, and aluminum as the biggest users of water. Other materials seem to have a minimal effect on the overall water input. This would be consistent with similar trends found in the production of materials phase.

The data for machining, the secondary process was not included for two main reasons. First, the data was presented in terms of kilograms of material removed, which cannot be compared to the approach for this assessment. And secondly, even the reports themselves disregarded the validity of the data by providing suggestions that, if the database become important, it should be investigated further. In other words, the machining data is not a reliable or a good indicated of water use.

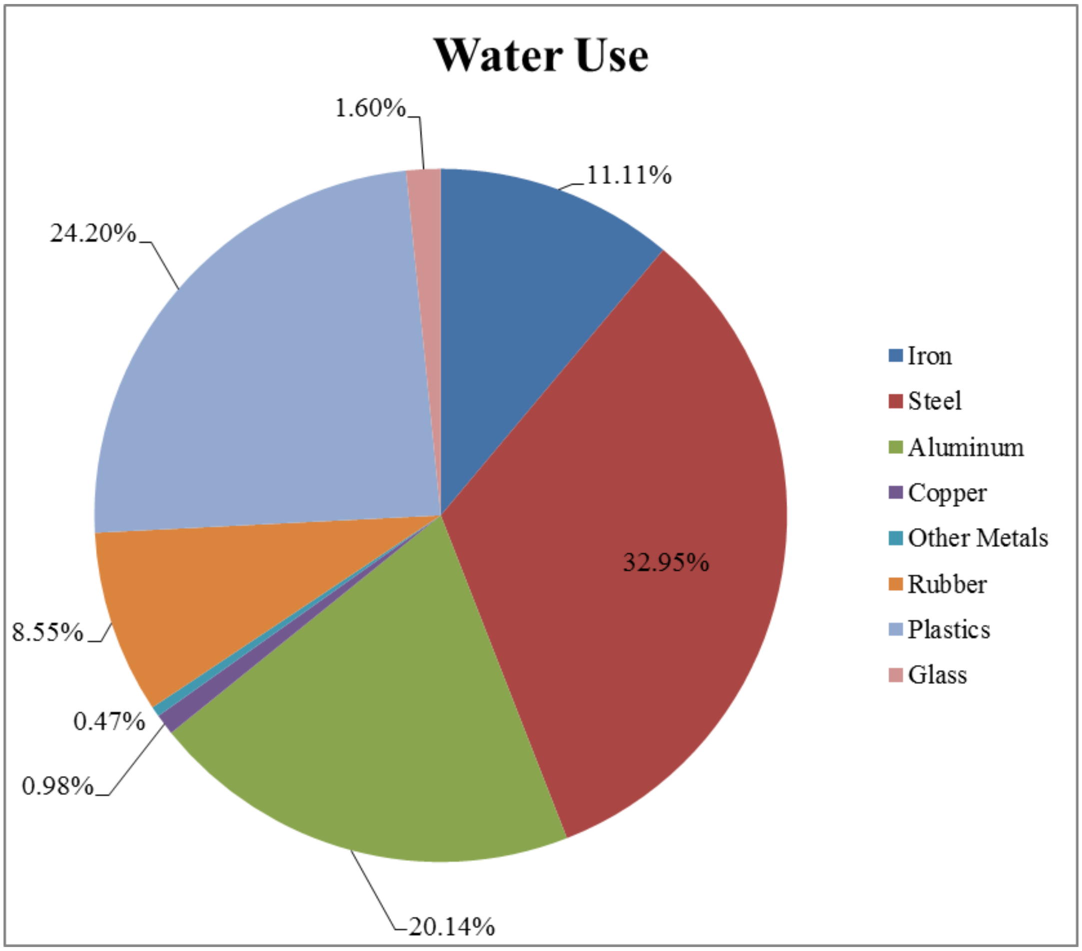

Figure 14: EcoInvent Water Use (Hischier 2007; Classen, Althaus et al. 2009)

Table 24: EcoInvent Data (Hischier 2007; Classen, Althaus et al. 2009)

| Material | Weight (Kg) | Primary Process | Report Number | Liters / Kg | Total Liters |
|---|---|---|---|---|---|
| **Cast Iron** | 194.82 | **Cast**<br>165.60 | **1069** | 22.83 | 3,781 |
| | | **Forged**<br>29.22 | **8303** | 3.53 | 103 |
| **Steel** | 598.97 | **Stamped**<br>419.28 | **8286** | 27.27 | 11,434 |
| | | **Forged**<br>23.96 | **8303** | 3.53 | 85 |
| **Aluminum** | 154.22 | **Cast**<br>117.21 | **1046** | 55.00 | 6,446 |
| | | **Forged**<br>35.47 | **8208** | 16.73 | 593 |
| **Copper** | 20.41 | **Drawn**<br>13.88 | **1178** | 24.40 | 339 |
| | | **Cast**<br>6.53 | **1159** | 0.56 | 4 |
| **Other Metals** | 7.26 | **Cast**<br>7.26 | **1069** | 22.83 | 166 |
| **Rubber** | 60.33 | **Compression Molded**<br>53.69 | **1853** | 49.52 | 2,659 |
| | | **Injection Molded**<br>6.64 | **1853** | 49.52 | 329 |
| **Plastics & textiles** | 181.44 | **Compression Molded**<br>23.59 | **1853** | 49.52 | 1,168 |
| | | **Injection Molded**<br>72.58 | **1853** | 49.52 | 3,594 |
| | | **Thermoset**<br>48.99 | **1815** | 49.52 | 2,426 |
| | | **Extruded**<br>29.03 | **1851** | 31.41 | 912 |
| | | **Other**<br>7.26 | **1853** | 49.52 | 359 |
| **Glass** | 39.92 | **Float Glass**<br>39.92 | | 14.00 | 559 |
| **Total** | 1,257.37 | | | | 34,956 |

## 4.10 Water Consumption for Metal Parts Production

### 4.10.1 Sample Supplier for Producing Metal Parts - Componenta

As an initial example, the environmental report published by "Componenta," was examined. Componenta is a metal sector company with international operations that casts, machines, and surface treats components and assemblies of metal. The group's customers are manufacturers in the machine building, heavy truck, automotive, construction & mining, agriculture and wind power industries (Componenta 2010).

The reason this company serves as a good initial basis for water consumption values is because they have a variety of operations that include cooling, processing, and cleaning. Additionally, they also make a clear distinction between their wastewater discharge, and water consumption. In their website, and yearly sustainability report released in 2010, they published numbers for production, water use, water consumption and material inputs. In other words, they have data for Input – Output, water use and water consumption. The only limitation to this data is that they don't differentiate the material output in more detail for the different metals (Componenta 2010). These numbers can be used as basis for the magnitudes and ranges of water consumption values that should be expected from other sources.

In their publications, Componenta reported that the foundry operations accounted for 95% of the wastewater, Table 25, that is generated (Componenta 2010). Using the total production data, Table 26, and the water use for outputs, Table 27, the percentage of total water use for both machine shops and forges can also be calculated to be 2.6% and 2.4% respectively.

Table 25: Componenta Total Wastewater & Total Water Consumption (Componenta 2010)

| Type of Water Distinction | m^3 |
|---|---|
| Wastewater | 396,401 |
| Water Consumption | 501,598 |
| Total Water Use | 897,999 |

Table 26: Componenta Production Outputs (Componenta 2010)

| Process | Production (Tons) |
|---|---|
| Foundries | 197,719 |
| Machine shops | 34,707 |
| Forge | 15,879 |

Table 27: Componenta Production Wastewater for Outputs (Componenta 2010)

| Process | Wastewater (Liter / Kilogram) |
|---|---|
| Foundries | 1.80 |
| Machine shops | 0.30 |
| Forge | 0.40 |

By far the largest single consumer of water was the Manisa aluminum foundry, which generated 81% of the Group's total waste water. The reason for the high consumption in Manisa is that more water was needed to wash off the penetrant fluid used in the testing of aluminum components (Componenta 2010).

If a similar percentage for water consumption is assumed, which would be expected to be the same order of magnitudes based on the percentages of water use and production for each of these aspects of manufacturing, a typical value for water consumption can be calculated as shown in Table 28. These numbers can be used as a reference for other expected water consumption values (Componenta 2010). It should be noted that, since Componenta did not differentiate between their outputs in terms of composition, these values should be taken to be magnitudes rather than exact expected numbers, especially for the foundry, in which aluminum and iron can have significantly different values for water consumption.

Table 28: Componenta Production Water Consumption for Outputs (Componenta 2010)

| Process | Water Consumption (Liter / Kilogram) |
|---|---|
| Foundries | 2.41 |
| Machine shops | 0.38 |
| Forge | 0.76 |

### 4.10.2 Foundries

4.10.2.1 Overview

Metal die casting has been described as the most direct and shortest route from component design to production. Almost any metal that can be melted can also be cast, and the design of the casting can be extremely flexible. This flexibility allows companies to produce simple or complex components of infinite variety (Tan and Khoo 2005). Production of cast components takes place in foundries. The molds that give the product its exterior shape are made of sand or produced of steel. Molding takes place on automatic molding lines, and only the very largest molds are made by hand. The molten metal, which has been melted in an electric or cupola furnace, is poured into the mold. After cooling and fettling, the product is ready for further processing. The foundries have the highest environmental impact in terms of natural resources. They use water for cooling, sand production, testing castings, paint, and sanitary water (Componenta 2010). Foundries can also use water during the processing of the parts after casting for quenching, finishing, etc. The sand is also partially made up of water (Colton 2009). Die casting uses significant quantities of energy, as well as materials like oil-based lubricants and cooling water. (Dalquist and Gutowski 2004).

Published sources placed casting as the biggest consumer of water, even if few focused on detailed analysis of the environmental effects, especially on the water use or water consumption. Reducing water use in casting operations would have the greatest effects on life cycle water consumption, especially in the wet scrubbers which is where most wastewater is produced in foundries, and would be particularly significant in regions where freshwater is a scarce resource (Martchek 2000; Stephens, Wheeler et al. 2001; Dalquist and Gutowski 2004). Figure 15 below shows an overview of the casting process: melt metal, pour and force liquid into mold, cool and solidify, remove from mold, and finish (Colton 2009).

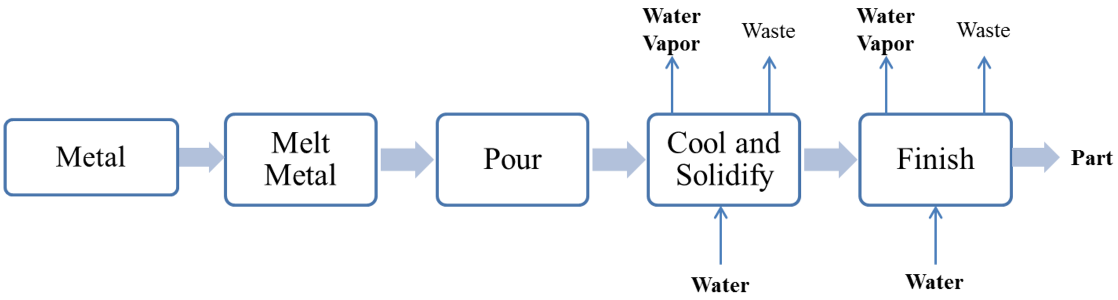

Figure 15: Overview of Casting Process (Dalquist and Gutowski 2004; Colton 2009)

### 4.10.2.2 Types of Casting

There are many types of casting currently being used in industry, for different parts, having different tradeoffs between dimensions, tolerances, surface finishes, etc. (Colton 2009). Table 29 below shows the different kinds used and the appropriate dominance in the market. As can be seen, sand casting dominates the market, so using the water consumption for this process would be the most representative of this stage in manufacturing.

Table 29: Types of Casting (Colton 2009)

| Type of Casting | Metals Processed by Casting |
|---|---|
| Sand Casting | 60% |
| Investment Casting | 7% |
| Die Casting | 9% |
| Permanent Mold Casting | 11% |
| Centrifugal Casting | 7% |
| Shell Mold Casting | 6% |

#### 4.10.2.3 Metal: Cast Iron

To produce metal casting, one of the most common processes, as shown in Table 29, was with the use of sand. Finding data for sand casting would provide the most representative value for water consumption in the production of cast iron components. One study on the foundry mass balance found that UK foundries consume 1.5 tons of water for each ton of cast product or 1.5 liters per kilogram of cast produced. Though no comparable estimate was found for US consumption, it should be in the same range on a ton per ton basis because the prevalence of green sand casting (water binder), iron processing (cupola use and therefore wet scrubber use), and the need for rapid cooling are similar in both countries (Dalquist and Gutowski 2004).

#### 4.10.2.4 Metal: Aluminum

The casting of aluminum components can have a great impact on the environment in terms of energy, emissions, and water consumption. Alcoa was chosen to determine a representative value for water consumption in the casting of aluminum parts for two main reasons. First, they provide various environmental reports showing their water consumption. Secondly, Alco is a global supplier of cold-finished, extruded aluminum products, and castings for the passenger car and truck markets. To determine water consumption, one of their plants in Fusina was analyzed. The plant, which includes a cast house and rolling mill, reduced water consumption 95 % by introducing a closed-loop water system. Historically, the plant used around 750 cubic meters of water per hour that was drawn from a local river. However, after the introduction of the upgrade, the only water lost was evaporated the cooling tower at rate of 40 cubic meters per hour (Alcoa 2007). Using 100 % percent of the yearly capacity of 45,000 tons per year, and assuming nonstop production, the water consumption for the plant would be the 7.8 liters per kilogram of aluminum (Alcoa 2012).

Even within a company, there is variability in terms of the data that is made publicly available. For Alcoa, this specific plant had a water consumption number for the production of aluminum products. However, in their sustainability report, Alco reported a water intensity value, or water consumption for the production of rolled sheets, to be 3.8 liters per kilogram. The water consumption from the sustainability report and that calculated from the plant in Fusina are higher than the water consumption for the casting of iron products. Because the water consumption from the sustainability report represented an average for Alcoa’s total worldwide operations, it will be used in the analysis in aluminum casting (Alcoa 2010).

#### 4.10.2.5 Metal: Copper

The process of melting copper includes a variety of materials which include concentrates, dust fluxes and revert in a furnace. One study conducted by the U.S. Geological Survey examined the world production of copper smelting and took an average for 65 % percent of world production to examine the inputs and outputs for the process. According to this report, 0.49 liters are consumed in the copper smelting process. Rather than being consumed for cooling, as is the main focus in other casting operations, the water was consumed in the sulfur recovery system (Goonan 2005).

#### 4.10.2.6 Other Metals

Other metals in a vehicle can include a wide spectrum of choices ranging from Zinc used to coat surfaces, to Magnesium, used to produce wheels. Similar to iron and aluminum, melted metal can be cooled by a pool of water to solid (Bleiwas and DiFrancesco 2010). For the representation for other metals, the water consumption of cast iron was selected from the section called 4.10.2.3 (Dalquist and Gutowski 2004).

#### 4.10.2.7 Water Consumption Summary for Metals Casting

Based on the previous sections, a summary of water consumption in the casting of metals can be developed, as shown in Table 30. As can be seen, the casting of aluminum parts consumes the most water regardless of which water consumption value is used from Alcoa (Alcoa 2007; Alcoa 2010; Alcoa 2012). The water consumption in the casting of steel was not included because in the manufacturing state of automobile production, steel is stamped or forged, but not directly cast (Sullivan, Burnham et al. 2010). Including water consumption in the casting of steel components would count the environmental impact of producing this material twice; once in the production of materials, and again in the production of parts.

Table 30: Casting Water Consumption Summary

| Material | Water Consumption (Liters / Kilogram) | Source |
|---|---|---|
| Cast Iron | 1.5 | (Dalquist and Gutowski 2004) |
| Aluminum | 3.8 | (Alcoa 2010) |
| Copper | 0.49 | (Goonan 2005) |
| Other Metals | 1.5 | (Dalquist and Gutowski 2004) |

### 4.10.3 Forging

#### 4.10.3.1 Overview

Forged components are manufactured on largely automated production lines. At the forges, the bars supplied by foundries are made into forging blanks. The blanks are forged, using hammers, into the correct shape. Water at these facilities is typically used for cleaning, lubrication, and cooling (Componenta 2010).

#### 4.10.3.2 Forging Lubricants

In forging, lubricant is used to improve quality and to increase the life of dies. Lubricants help to reduce friction from the metal to metal interaction which allows the flow to occur in a smooth and controlled way, and keep the process cool by removing undesirable heat. For this reason, lubrication is vital for successful sheet metal forming. It helps to reduce tonnage requirements, extends tooling life, and improves product quality. Lubricants range from light mineral oils to high viscosity drawing compounds. They may be oil base, water soluble, or synthetic materials depending on the material being forged and the requirements for the different operations (SME 2003).

#### 4.10.3.3 Application of Lubricants

When preparing lubrication in current forging practice, many forgers simply guess the quantity of raw lubricant to dump into the mixing tank when it is running low and likewise guess the amount of water to add on top. If the lubricant is not mixed for an adequate time period, the heavy, raw lubricant from the bottom of the tank is used first, resulting in excessive consumption of lubricant solids, while later mixtures have inadequate solids. A lubricant's ability to adhere is dependent externally on die and work piece temperature and inherently on lubricant formulation and lubricant dilution ratio. The less the lubricant is diluted, the better it will adhere but cooling and heat transfer will be poorer. If a lubricant with too high solids (low dilution ratio) is applied, and especially when dies are cold, the lubricant builds up in die cavities, resulting in under-fill. If a lubricant with a too-high dilution ratio is applied, there are not enough solids the lubricant will not adhere, and the dies overheat. Typical application systems today consist of a pressure pump system used to deliver lubricant into a lubricant manifold that feeds several lubricant lines with spray nozzles or flooding pipes.(Liu 2007)

#### 4.10.3.4 Water Consumption for Forging

As explained in section 4.10.3.3, the amount lubrication applied during forging varies from manufacturer to manufacturer and is highly intuitive rather than an exact science. No data that differentiated among the different metals could be found in literature, government reports, or even on company information relating to recommended quantity of water use, to the expected replacement rate used for lubrication, or for cleaning. However, the value used in forging obtained from the Componenta Sustainability Report of 0.76 liter per kilogram is to be utilized for forging operations as described in section 4.10.1 (Componenta 2010). Although it does not provide an exact number, this value at least provides a general magnitude which can be used for comparison in the analysis.

### 4.10.4 Metal Working

#### 4.10.4.1 Overview

The majority of parts comprising the bodywork of a current mass produced motor vehicle are shaped by press working, i.e. blanks are made to conform to the required contour largely by a mixture of drawing and stretching within the initial main draw die. Controls help to ensure the pressure inside the press shop is maintained, and that washing equipment works properly as blanks are automatically fed into the installation (Davies 2003).

#### 4.10.4.2 Metal Working Lubricants

The main type of lubrication used in metal working is boundary lubrication. The main function is to interpose between the work metal and the tool to minimize metallic contact. The resistance of the metal stock to the forces exerted by the moving dies creates friction. In drawing, for instance, cooling is also used to control function.  Lubricants range from light mineral oils to high viscosity drawing compounds. The lubricants may be oil base, water soluble, or synthetic materials (SME 2003).

### 4.10.4.3 Stamping Steel

Metal stamping is the industrial process of stamping or shaping designs on sheets of metal. A metal sheet alloy is stamped or pressed on a machine using dies and a hydraulic machine to create the designs. This process can be a single stage operation where every stroke of the press produces the desired form on the sheet metal part, or could occur through a series of stages. Lubricants are sometimes used, especially when forming steel parts because more heat is generated due to the high friction. For best results when working steel, synthetic lubricants or a petroleum based lubricant should be applied over the dry material (Joseph 2005). These lubricants can include oil-based fatty acids, waxes, polymers, and soaps. As a general rule, water-based lubricants are not recommended. And since no water is used for lubrication, no water is consumed (1990; Joseph 2005). Although it could be argued that water is sometimes used for cleaning the parts after deformation, because of the lower temperatures associated with stamping, compared to the melting point of steel, water is typically not evaporated. Cleaning the finish parts creates wastewater, which does have an impact, but does not consume much water according to the scope defined for this analysis. Water use for cleaning in this process is highly variable and no exact data could be found for recommended or experienced flow rates.

### 4.10.4.4 Drawing Copper

Several water-soluble synthetic or occasionally water-soluble oil lubricants used to roll form aluminum are applicable for copper based metals. High penetrating, high wetting, properties are preferred (Joseph 2005). Copper allows water to be used as a base lubricant for high speed operations (2010). To determine the water consumption for the drawing of copper, two sets of approaches were used. One was to gather information directly from a published article focusing on the emulsions for the drawing of copper wire and the other was to calculate flow rates based on maximum outputs for a copper wire operation using machinery specifications.

In the published article, a lubricant was diluted in water during a series of tests at an average of 6 % percent composition. The lubricant was said to be consumed at an average of 0.8 kilograms per ton of copper wire manufactured. Extending this amount of coolant consumption to the water in solution, the water consumption can be calculated to be 0.013 liters per kilogram of copper wire manufactured. This value focuses on loss due to evaporation and other factors while pulling the wire through a die (Belosevich and Svidovskii 1997).

In the machinery specifications, a medium size copper wire making machine with a maximum flow rate for a 6 mm diameter wire at 12 meters per second, or 3.04 kilogram per second, was examined (Komax Corporation 2011). This machine was coupled with a water recycling unit that would filter out particles after each drawing operation with a maximum flow rate of 21 gallons per minute or 1.325 liters per second (Filtertech 2011). The lubricant use for copper drawing turns out to be 0.43 liters per kilogram of material processed of which, using the same average of water consumption from the published paper, 94 % percent would be water, to give a water use number of 0.4 liters per kilogram of copper drawn. Assuming a 3% loss rate due to evaporation and replacement requirements, typical of other operations like machining, the calculated water consumption rate would be 0.012 liters per kilogram of material used (Gedlinske 1997; Dahmus and Gutowski 2004). Adjusting the replacement rate as well as lowering the inlet lubricant flow from the filtration system would yield results similar to those from the published paper. Regardless of which approach is used for copper drawing, the process has a minimal effect in terms of water consumption.

#### 4.10.4.5 Water Consumption Summary for Metal Working

Based on the previous sections, a summary can be developed for metal working operations as shown in Table 31. As can be seen, the effect of these values in the overall water consumption for the production of parts is minimal. Although their water use can be higher, because of the low temperatures in these processes, at least compared to other operations, the water loss is minimal.

Table 31: Water Consumption for Metal Working Operations

| Process & Materials | Water Consumption (Liters / Kilogram) | Sources |
|---|---|---|
| Stamping Steel | 0 | (1990; Joseph 2005) |
| Drawing Copper | 0.012 | (Gedlinske 1997; Dahmus and Gutowski 2004; Filtertech 2011; Komax Corporation 2011) |

### 4.10.5 Machining

#### 4.10.5.1 Introduction

After casting or forming, parts may be sent to a machine shop. These components may be surface treated or they may have certain details added. At least one environmental report from an automobile parts manufacturer suggest that machine shops do not impose a significant load on the environment concerning water use and specially water consumption, especially when compared to casting operations as described in section 4.10.1 (Componenta 2010).

Machining is a material removal process that typically involves the cutting of metals using various cutting tools. It is a process that is particularly useful due to its high dimensional accuracy, flexibility of process, and cost-effectiveness in producing limited quantities of parts. Among manufacturing processes, machining is unique in that it can be used both to create products and to finish products (Dahmus and Gutowski 2004).

In machining, almost all of the energy expended in cutting is transformed into heat. The deformation of the metal to create chips and the friction of the chip sliding across the cutting tool produce heat. The primary function of cutting fluids is to cool the tool, work piece, and chip, to reduce friction at the sliding contacts, and to prevent or reduce the welding or adhesion on the contact edges that causes a built-up edge on the cutting tool or insert. Cutting fluids also help prevent rust and corrosion, and they flush chips away (Fox Valley Technical College 2000). An overview of the water use in machining can be found below in Figure 16. Basically, water helps to reduce tool wear by removing heat, some of it in the form of evaporation.

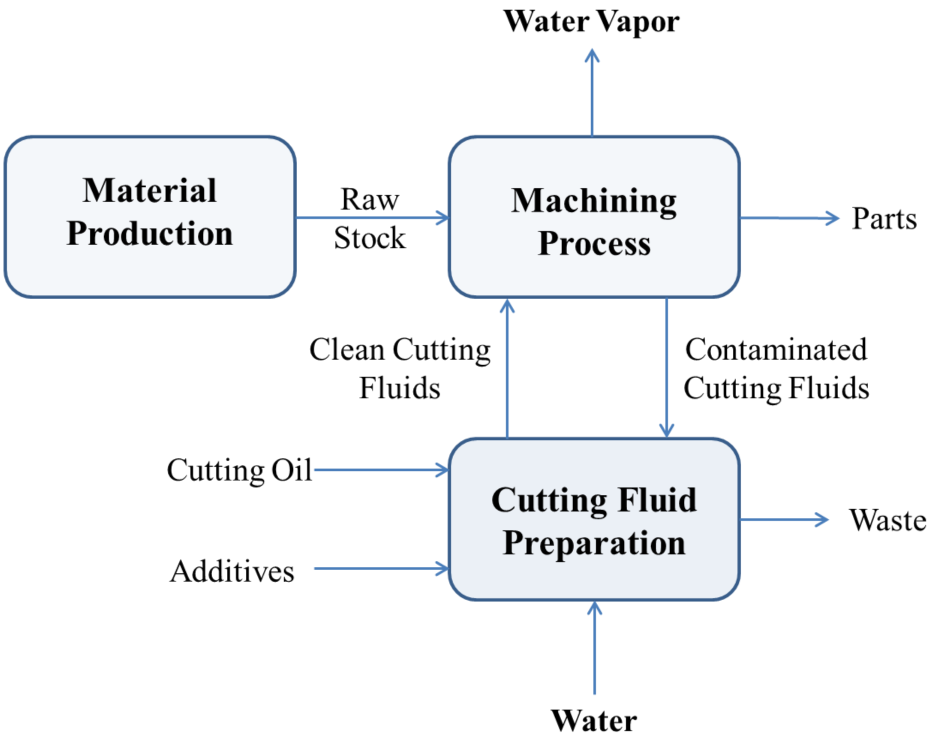

Figure 16: Machining Water Use Overview (Fratila 2010)

### 4.10.5.2 Cutting Fluid Types

Cutting fluids can be broken into four main categories: straight cutting oils, water miscible fluids or soluble oils, gasses, and paste or solid lubricants. Two of the three (chemical-based and emulsions) are primarily water. Water is the best fluid for cooling. It has the best ability to carry heat away. Water, however, is a very poor lubricant and it causes rust. Oil is great for lubrication but very poor for cooling, and it is also flammable.

If water and oil are combined, the best of both is obtained, which minimizes the weaknesses. Water-soluble fluids have been developed that have good lubrication, cooling ability and rust and corrosion resistance (Fox Valley Technical College 2000).

The choice of a cutting fluid depends on many complex interactions including the machinability of the metal; the severity of the operation; the cutting tool material; metallurgical, chemical, and human compatibility; fluid properties, reliability, and stability; and finally cost. Other factors also affect results. Some shops standardize on a few cutting fluids which have to serve all purposes. In other shops, one cutting fluid must be used for all the operations performed on a machine (Oberg, Jones et al.). However, under normal machining conditions certain generalizations can be made which facilitate the calculations for both water use and water consumption for various materials and machining operations. A summary of the assumed simplified cutting fluids use for different machining operations can be found in Table 32. As can be seen, most materials use some form of soluble oil which varies in composition. Some of the metals that are machined under dry conditions may have oil based oils applied for lubrication.

Table 32: Coolant Use (Oberg, Jones et al. ; Fox Valley Technical College 2000)

| **Material** | **Milling** | **Drilling** | **Tapping** | **Turning** |
|---|---|---|---|---|
| Cast Iron | Dry Cutting | Dry Cutting | Dry Cutting | Dry Cutting |
| Steels (Carbon, Alloy & Others) | Soluble Oil | Soluble Oil | Soluble Oil | Soluble Oil |
| Aluminum | Soluble Oil | Soluble Oil | Soluble Oil | Soluble Oil |
| Copper | Dry Cutting* | Dry Cutting* | Dry Cutting* | Dry Cutting* |
| Zinc | Straight Oil | Straight Oil | Straight Oil | Straight Oil |
| Other Metals | Dry Cutting* | Dry Cutting* | Dry Cutting* | Dry Cutting* |

*Different types of oil may be applied for difficult machine operations

### 4.10.5.3 Cutting Fluid Operation

Typically, machines and grinders are flood cooled which means that water is flooded over the work area as shown in Figure 17. This cools the work and washes particles out of the way. The liquid runs over the work area and then down the machine where it collects in a sump at the bottom of the machine (Gedlinske 1997). Machine coolant filtering is something many machine shops have been doing for years. This means that most of the coolant fluid is recycled and reused during the machining operations The recent development of smaller, less expensive and more efficient filter units combined with the need for greater quality and tighter government regulations seem to be pointing to the day where every machine will have a machine coolant filter just as every automobile has an oil filter (Gedlinske 1997).

Figure 17: Machine Coolant (Fox Valley Technical College 2000)

### 4.10.5.4 Cutting Fluid Composition

The vast majority of machining in automobile manufactures, General Motors for example, is done using water-based soluble oils (Dasch, D'Arcy et al. 2005) The fluid applied, is typically 90% to 95% water and 5 to 10% machine coolant (Fox Valley Technical College 2000). For this analysis, it will be assumed that the coolant consists of

90 % water and 10% machine coolant, unless otherwise stated, because it is often cited as a reasonable cutting fluid composition and because it assumes a conservative approach to water consumption (Oberg, Jones et al. ; Diniz, Micaroni et al. 2010). The liquid is pumped out of the sump and constantly recirculated at rate ranging from 2 to 19 liters per minute depending on the material and type of machining operation (Oberg, Jones et al. ; Diniz and José de Oliveira 2004). A summary of the coolant composition and typical flow rates can be found below in Figure 18. These flow rates will be coupled in later sections to different materials and machining operations to determine water use and water consumption.

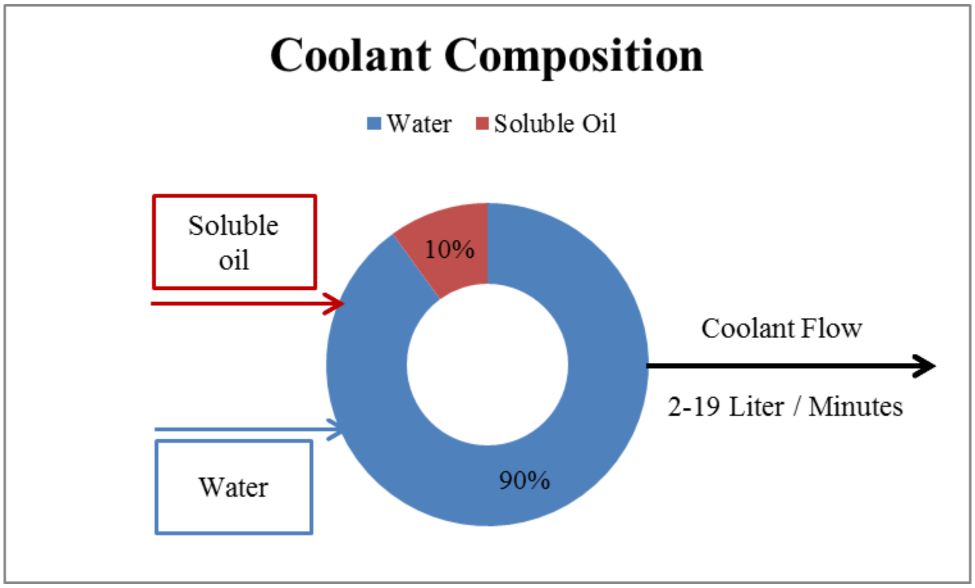

Figure 18: Coolant Fluid Composition and Flow Rate

#### 4.10.5.5 Types of Machining Operations

There are three main types of machining in use today in terms of application of cooling fluids: wet machining, dry machining, and near-dry machining (NDM), also known as minimal quantity lubrication (MQL). The differences between these machining operations lie in how much and under what conditions cooling fluids are applied.

In wet machining, high flow rates of cooling fluid, up to 19 liters per minute, are applied during operation. It has the advantage of good part quality, low tool wear and high tool life which contributes to an economical cutting speed and generally high efficiency of production (Galanis, Manolakos et al. 2008).

In dry machining, no coolant fluids are generally applied during operation. This results in cleaner parts, no waste generation, reduced cost of machining, and reduced cost of chip recycling (no residual oil). However, large capital expenditure required to upgrade equipment (Davim and Astakhov 2008). High cutting forces and temperatures in dry machining may also cause the distortion of parts during machining.

Near-dry machining (NDM) formerly known as minimum quantity lubrication (MQL) machining, was developed to provide at least partial solutions to the listed problems with dry machining (Davim and Astakhov 2008). In this operation, fluids are typically applied at high pressures and at reduced flow rates, down to 2 liters per minute, compared to wet machining. The cooling media is supplied as a mixture of air and an oil in the form of a mist, which is a gaseous suspension into air of solid or liquid particles (Davim and Astakhov 2008).

#### 4.10.5.6 Initial Water Consumption Assessment for Machining

The values for overall water consumption vary depending on the source. Based on the environmental report from Componenta described in 4.10.1, the water consumption for their machining operations can be in the order of 0.30 liters per kilogram of process material (Componenta 2010). One report in EcoInvent, on the other hand, listed the operations of mechanical engineering machines evaporating an of average 1.25 liters water per kg of process material. However, the assumptions made for the scope of this data are not clearly defined. This value can be seen as an upper boundary for water consumption showing the worst case scenario (Steiner and Frischknecht 2007).

What was consistent across all sources is that most of the water is in the coolant. Evaporation of water means a loss 3% to 10% of water daily use in the coolant

(Gedlinske 1997; Dahmus and Gutowski 2004). For water consumption calculations, unless otherwise stated, a 3% loss in water consumption due to evaporation will be assumed as a conservative value based on the flow rates found.

#### 4.10.5.7 Cast Iron

As mentioned before, cast iron is typically processed with dry machining so no coolant fluid is used and no water consumption will be calculated. Some operations may use coolant fluid for faster machining, but, under normal conditions to produce expected results, it is not necessary to apply cutting fluids (Oberg, Jones et al. ; Fox Valley Technical College 2000; Dasch, D'Arcy et al. 2005).

#### 4.10.5.8 Steel

The flow rate of steel varied significantly depending on the application, type of steel and machining operation. In one example, the cutting fluid was applied at a rate of 4.3 liters per min, a recommended value for turning and grinding steel operations (Diniz and José de Oliveira 2004). Others used higher values of applied cutting fluids as high as 11 liters per minute (Diniz, Micaroni et al. 2010). For this analysis, it will be assumed that the maximum flow rate, 19 liters, is applied to steel parts as a worst case scenario.

In one paper, Steel transmission output shafts were machined at a rate of one shaft every 2 minutes, each weighting 2.5 kilograms. Assuming a flow rate of 19 liters per minute of coolant, at a composition of 90% water and evaporation rate of 3% on the water, the water consumption per shaft would be 1.03 liters or 0.4 liter per kilogram (Dasch, D'Arcy et al. 2005).

#### 4.10.5.9 Aluminum

For aluminum, one study was selected which focused on the machining of cast aluminum engine blocks and engine heads. The paper explained that one shift produced 821 heads and 313 blocks (Dasch, D'Arcy et al. 2005). On a global average, an aluminum 4-cylinder engine block weighs about 19 kg while a small cylinder head can weigh 10.5

kg (Murphy 2006; Dart Machinery 2010). Multiplying the number of parts with the weight of the components, the total production weight can be found to be 14,567.5 kg. The machining fluid was a Castrol WS3-908E semisynthetic fluid used at 10% concentration by volume. 150,000 liter sumps fed the block and head areas for this shift (Dasch, D'Arcy et al. 2005). Using a 90 % composition of water, and a 3 % total evaporation per day, the total water consumption would be 4,050 liters for the production of these parts. Coupling the total production by weight and the total consumption, it can be seen that the water consumption for the machining of aluminum parts is about 0.28 liters per kilogram, which is consistent with other information found in section 4.10.1. A diagram depicting the production of aluminum parts can be found below in Figure 19. On the other hand, assuming a composition of 95 % water, with an evaporation loss rate of 10 %, the water consumption for this operation could be up to 1 liter per kilogram of material.

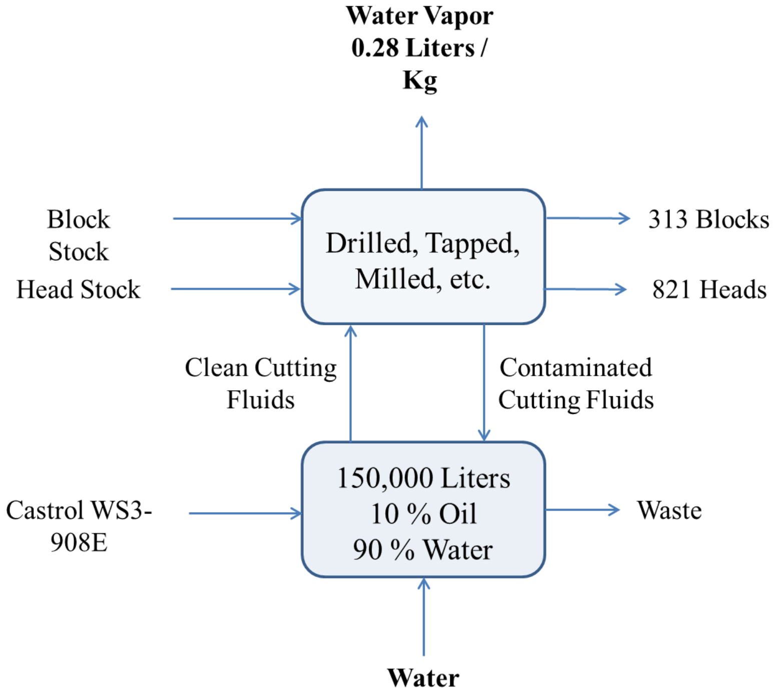

Figure 19: Overview of Aluminum Machining Water Consumption (Gedlinske 1997; Dasch, D'Arcy et al. 2005; Murphy 2006; Dart Machinery 2010)

#### 4.10.5.10 Copper

Although copper is frequently machined dry, a cooling compound is recommended. Other lubricants that have been used include tallow for drilling, gasoline for turning, and beeswax for threading (Oberg, Jones et al.). Either way, no water is typically used in the machining of copper components.

#### 4.10.5.11 Other Metals

For zinc and other metals like magnesium and nickel, the machining operations are mostly performed without a lubricant. For particular work, especially deep drilling and tapping, a lubricant such as lard oil and kerosene or a 50-50 mixture of kerosene and machine oil may be used; these would contain no water and therefore no water consumption would be associated with them (Oberg, Jones et al. ; Fox Valley Technical College 2000). Although this assessment can vary from case to case, it is a generality fitting for this analysis, especially when the worst case scenarios are being assumed for the machining of steel and aluminum materials, which encompass most of the vehicle.

#### 4.10.5.12 Water Consumption Summary for Machining

Based on the previous sections, a summary of the water consumption of machining for the various materials in a vehicle can be established as shown below in Table 33. It should be noted that these values provide a trend in water consumption rather than absolute values. There is much variability in how parts are machined which would result in either higher or lower water consumption values. For instance, wet machining was used for calculating the water consumption values. Using dry or even near-dry machining would significantly reduce these values. Different losses due to evaporation or through chips, scrap, and work pieces leaving the material removal process may also add to the loss of cutting fluid and water. Regardless of the assumptions, it is clear that a fair amount of cutting fluid is lost through everyday activities (Dahmus and Gutowski 2004). What can be seen is that the machining water consumption values are similar in magnitude to those presented in section 4.10.1 for Componenta, a supplier of automobile parts (Componenta 2010).

Even though machining of copper and other metals is not part of the production assessment set forth in a previous section, it was still included for completeness. What can be seen is that, because the machining of these metals is performed with an oil based coolant, it consumes no water, so even if it had been included in the analysis of material flows into this process, it would have had no effect on the accounting of water consumption (Oberg, Jones et al. ; Fox Valley Technical College 2000).

Table 33: Machining Water Consumption Summary

| Material | Water Consumption (Liters / Kilogram) | Sources |
|---|---|---|
| Cast Iron | 0 | (Oberg, Jones et al. ; Fox Valley Technical College 2000; Dasch, D'Arcy et al. 2005) |
| Steels (Carbon, Alloy & Others) | 0.4 | (Diniz and José de Oliveira 2004; Dasch, D'Arcy et al. 2005; Diniz, Micaroni et al. 2010) |
| Aluminum | 0.28 | (Dasch, D'Arcy et al. 2005; Murphy 2006; Dart Machinery 2010) |
| Copper | 0 | (Oberg, Jones et al.) |
| Other Metals | 0 | (Oberg, Jones et al. ; Fox Valley Technical College 2000) |

### 4.10.6 Water Consumption Summary for Metals Components

Based on the information presented in the previous sections, a summary of the water consumption in the primary and secondary processing of metal parts is shown in Table 34. As can be seen, the casting of metal components has the highest water consumption values. This is because of the higher temperatures required for treating the materials, requiring more water for cooling. The machining of steel components consumed the most water for the secondary processing of metals as shown in Table 35.

Table 34: Water Consumption for Primary Processing of Metals

| Material | Primary Process | Liters / Kg |
|---|---|---|
| Iron | Cast | 1.50 |
| | Forged | 0.76 |
| Steel | Stamped | 0.00 |
| | Forged | 0.76 |
| Aluminum | Cast | 3.80 |
| | Forged | 0.76 |
| Copper | Draw | 0.01 |
| | Cast | 0.49 |
| Other Metals | Cast | 1.50 |

Table 35: Water Consumption for Secondary Processing of Metals

| Material | Primary Process | Secondary Process | Liters / Kg |
|---|---|---|---|
| Iron | Cast | Machined | 0.00 |
| | Forged | Machined | 0.00 |
| Steel | Stamped | Machined | 0.40 |
| | Forged | Machined | 0.40 |
| Aluminum | Cast | Machined | 0.28 |
| | Forged | Machined | 0.28 |

### 4.10.7 Data Variability

As can be seen by reviewing each of the previous sections, water consumption values for the processing of metal parts are limited, and many of these had to be calculated by coupling flow rates of coolants with evaporation rates. However, some variability can be shown, especially for the metals having the biggest impact, iron and aluminum, shown in Figure 20 and Figure 21 below. The figures also compare the magnitudes for water consumption. The processes that did not consume water directly were excluded. Also, since water use was mostly determined from the EcoInvent database, it was not added.

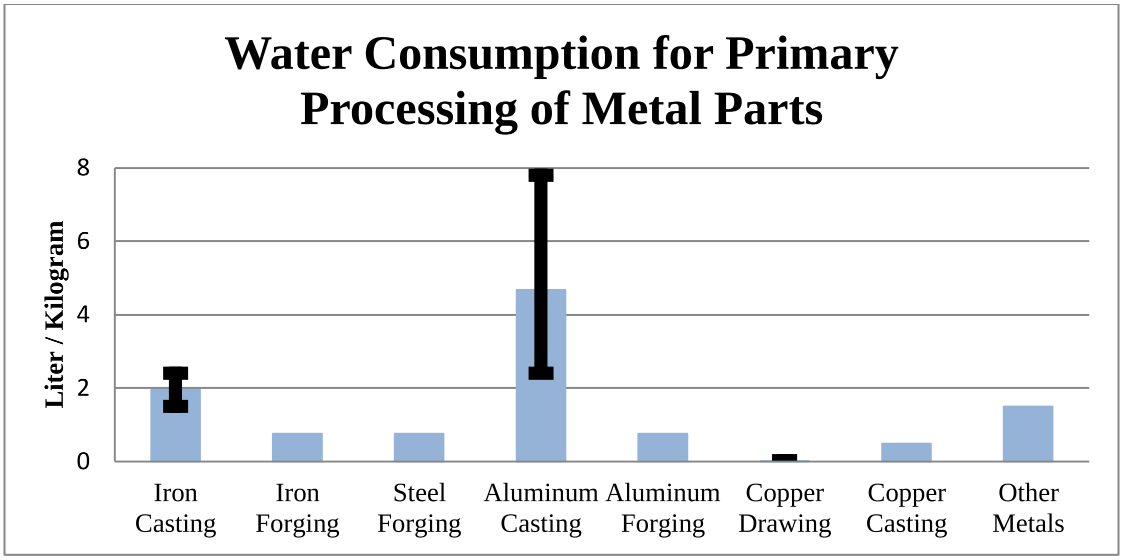

Figure 20: Water Consumption for the Primary Processing of Metals

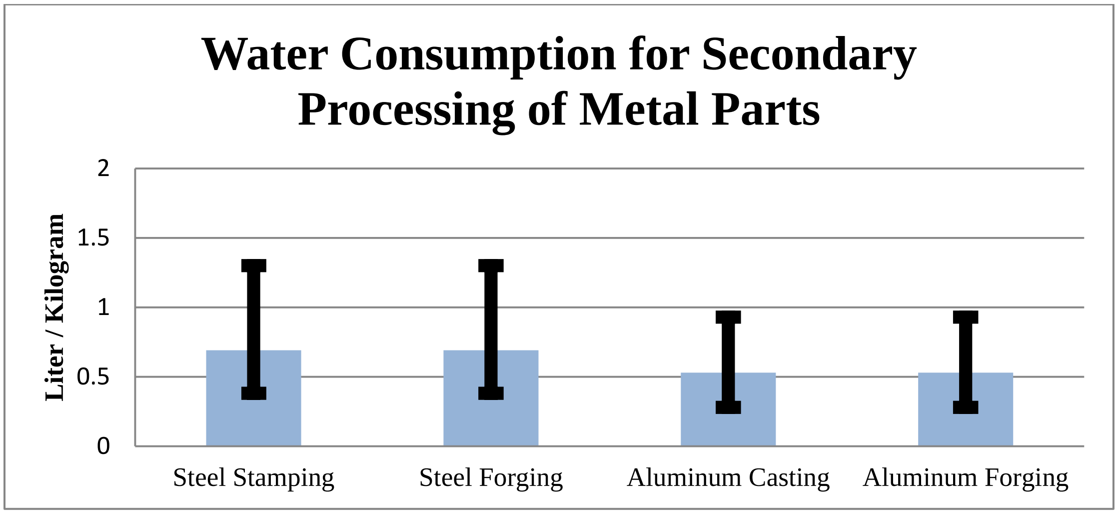

Figure 21: Water Consumption for the Secondary Processing of Metals

## 4.11 Water Consumption for Nonmetal Part Production

### 4.11.1 Injection Molding for Plastics

Injection molding is one of the most widespread manufacturing processes in use today. This process involves melting polymer resin, in an injection molding machine, together with additives, and then injecting the melt into a mold, cooled by air or water.

Once the resin is solidified, the mold opens and the part is ejected. (Thiriez 2006). At first glance, injection molding may appear to be a relatively benign process with respect to the environment. However, when calculating the environmental cost of injection molding one must also take into account the ancillary processes (Thiriez 2006).

The amount of water used in cooling depends largely on the material properties of the plastic being molded (Rosato, Rosato et al. 2000). By taking into account the heat transfer coefficient and inlet temperature of the various plastics, along with the heat carrying capacity of water, the heat generated in the hydraulic system, and the expected heat lost throughout the equipment, a set of guidelines for water flow requirements in cooling in terms of liters per kilogram can be established. As an average for the different plastics, a flow rate of 5.3 liters of water of chilling per 1 kilogram of material produced is recommended (Rosato, Rosato et al. 2000). A comprehensive table listing the required flow rates for the different plastics can be found below in Table 36 below. These flow rates only take into account water use directly to cool the materials and machinery. If there were additional uses of water, say for cleaning the parts after manufacturing, they would not be accounted for using this approach. However, as it will be shown in later sections, the additional water consumption associated with a more inclusive approach to water flow metering in the production of nonmetals is minimal and within the same magnitude.

Table 36:Water Flow Rate for Injection Molding of Plastics (Rosato, Rosato et al. 2000)

| Material | Flow Rate (Liter / Kg ) |
|---|---|
| Polyethylene | 3.78 |
| Polypropylene | 4.4 |
| PVC | 5.66 |
| ABS | 6.29 |
| Polystyrene | 6.29 |

Many injection molding factories have complex cooling systems. The main types are open-circuit water cooling systems with an evaporation-type cooling tower, closed-circuit water cooling systems with compression-type refrigeration machines, and composite systems. Open-circuit cooling systems operating exclusively with cooling towers were very popular in the past, but they are not very efficient. More effective systems are generally being utilized by manufactures today which recycle most of the water at a minimal loss. As a result of evaporation and slime formation, an estimated maximum 3 % of the circulated water is lost and must be replenished (Rosato, Rosato et al. 2000). Coupling the average recommended water flow rate for plastics with the water lost to evaporation, the water consumption for injection molding can be calculated to be 0.16 liters per kilogram. A more comprehensive table for all of the plastics can be found in Table 37. As can be seen, the calculated water consumption for the different plastics injection molding is minimal compared to that of some of the metals mentioned previously. This is because plastics have much lower melting points and thus require much less cooling so they consume less water.

Table 37: Water Consumption for Injection Molding of Plastics (Rosato, Rosato et al. 2000)

| **Material** | **Evaporation (Liter / Kg )** |
|---|---|
| Polyethylene | 0.11 |
| Polypropylene | 0.13 |
| PVC | 0.17 |
| ABS | 0.19 |
| Polystyrene | 0.19 |

### 4.11.2 Compression Molding for Plastics

In the most common approach, a preheated preform or tablet is placed in an open, heated, mold half that is held in a molding press, which usually operates vertically. The press ram descends with the force half of the mold, compressing the preform, so that the material flows to fill the entire mold cavity (Bralla 2007). The heat of the mold, and that added by the friction of the molding process, causes the material to polymerize, changing from a somewhat pasty state to a strong, solid state. The mold can be opened and the part removed (Bralla 2007).

Because the machinery used in compression molding is similar to that of injection molding, and because the materials have similar cooling requirements, the water consumption for molding is relatively similar to that for injection molding. So, for compression molding, the water consumption from injection molding from section 4.11.1 will be used.

### 4.11.3 Thermoset

In this process reinforcing fibers are placed to cover a plastic film carrier which lies on the surface of a belt conveyor. A liquid resin, most commonly polyester, is applied to the reinforcing material. The resins used usually incorporate several additives: colorants, UV stabilizers flame retardants, and fillers. A top film is applied. The resin-fiber mix on the film is conveyed to a pressure roller that bears against it, kneading it and ensuring that the fibers are fully wetted. After curing, the plastic films are stripped from the top and bottom of the laminate, edges are trimmed, and pieces are cut to length (Bralla 2007).

Out of many companies that produce thermosets, Dow Chemical provided the most comprehensive water use and water consumption information for their products. According to their sustainability report, the water consumed in their production was 0.40 liters per kilogram, Their water use was higher than that, but they recycled or treated up to 85 % percent of the water they use in their operations (Dow Chemical 2010). As it will be shown in later sections, this value for water consumption is similar to that for other.

### 4.11.4 Extrusion

Extrusion is the process of forcing a heated, semisolid plastic through a die whose cross-sectional shape it retains when it cools and solidifies. The operation is normally continuous. Thermoplastic material in granular form is fed from a hopper to the heated barrel of the extruder. A rotating screw transports the material through the barrel and mixes it as it melts, providing a uniform flow rate. The temperature of the material, as it reaches the extruding die, is uniform throughout. The material exiting from the die is cooled by air blast, water spray, or water trough, so that it hardens, forming a product of constant cross section and indefinite length (Bralla 2007). As is the case in to injection molding, a set of cooling water guidelines in terms of liters per kilogram of plastic can be established as shown below Table 38. The average water flow rate per kilogram is 9.02, which is in the same magnitude as the other process to produce nonmetal parts. Using an evaporation rate of 3 % percent for the water flow rate yields the water consumption found in Table 39. The average water consumption is 0.27 liters per kilogram of plastic extruded (Rosato, Rosato et al. 2000).

Table 38: Water Flow Rate for Extrusion (Rosato, Rosato et al. 2000)

| Material | Flow Rate (Liter / Kg ) |
|---|---|
| Polyethylene | 8.18 |
| PVC | 9.44 |
| ABS | 9.44 |

Table 39: Water Consumption Rate for Extrusion (Rosato, Rosato et al. 2000)

| Material | Evaporation (Liter / Kg ) |
|---|---|
| Polyethylene | 0.25 |
| PVC | 0.28 |
| ABS | 0.28 |

No industry data could be found for extrusion molding, although it is believed that the water consumption value is in the same magnitude and would yield similar values. It can also be seen that because of the small amount of material that is actually extruded, having a slightly different value for water consumption would yield minimal, almost negligible, changes in the overall water consumption in this stage for the life of a vehicle.

### 4.11.5 Injection and Compression Molding for Rubber

Because of the differences in material properties between rubber and plastics for both processing and cooling, additional data points were located for comparison using the production of tires as a basis. The average car tire consists of a variety of materials but, typically, over 50 % is rubber (Sullivan, Burnham et al. 2010). So, to determine the water consumption for injection and compression molding for rubber, several tire manufactures were investigated. Two major companies provided water numbers used in the analysis: Michelin and Pirelli. These companies published data for how much water was “consumed” in the production of their tires. However the numbers that they made publicly available were typically water use or water withdrawal (Michellin 2010; Pirreli 2010). As can be seen from Table 40, with an average of 13.9 liters per kilogram for rubber, these values are similar in magnitude to those for plastics as shown in Table 38, with an average of 5.3 liters per kilogram. One reason that the average water use based for manufacturers of rubber tires is higher is because they may include other processes, like cleaning, which are not directly accounted for when examining just the machinery and cooling requirements based material properties and machinery efficiency. Cleaning parts during the manufacturing stage does not consume much water even if it does create a great deal of wastewater. Another reason for the difference in water use between the production of rubber tires and the water use calculated for plastics in early sections is the fact that the tire maker’s typical deal with other material during production, such as steel wiring , and these may have higher water requirements. The manufacturing of rubber is also more energy intensive and thus requires more water for cooling and processing (Rosato, Rosato et al. 2000).

Table 40: Tire Water Use

| **Water Use (Liters / Kg)** | **Source** |
|---|---|
| 11.8 | (Michellin 2010) |
| 16 | (Pirreli 2010) |

If the company water use average were to be coupled with the evaporation rate previously mentioned of 3% for plastics from section 4.11.1 , the water consumption would be 0.42 liters per kilogram (Rosato, Rosato et al. 2000). Although increasing the evaporation rate would increase the water consumption for the production of rubber components, its effect, like that of plastic parts, would be insignicant in the production of parts or in the entire life cycle of a vehicle, because of the small amount this material actually used in a vehicle compared to the amount of metals.

### 4.11.6 Glass

Water in the glass manufacturing process is used for three main ways: cooling, cutting, and polishing. Cooling helps to maintain the machinery and solidifies the material after processing. Cutting activities can give rise to dust emissions, which are controlled by cutting under liquid. Polishing uses water to wash the material. One company's sustainability report was examined to determine the water use in the production of glass, a. The company reported a water use of 2 liters per kilogram of glass. They mentioned that most of the water used for cleaning and cooling operated in a closed loop and therefore was recycled within their facilities (NSG Group 2010). Using a 90 % water reuse rate, typical for industrial applications that recycle water as seen in the production of steel and other materials, the water consumption for glass production can be taken to 0.2 liters per kilogram of float glass produced (Nippon Steel 2010). This recycling rate does assume a very efficient system with best available technology.

### 4.11.7 Water Consumption Summary

Based on the information presented in the previous sections, a picture for the water consumption in the manufacturing of plastics, rubber, and glass can be created as shown in Table 41. As can be seen, relative to the water consumption in metals, the effect of plastics and rubber is minimal. This is because low temperatures are required for treating the materials, requiring small amounts of water for cooling, and because relatively low energy intensive manufacturing processes involved.

Table 41: Water Consumption for Plastics and Rubbers

| Material | Primary Process | Liters / Kg | Sources |
|---|---|---|---|
| Rubber | Compression Molded | 0.42 | (Rosato, Rosato et al. 2000; Michellin 2010; Pirreli 2010) |
| | Injection Molded | 0.42 | |
| Plastics | Compression Molded | 0.16 | (Rosato, Rosato et al. 2000) |
| | Injection Molded | 0.16 | |
| | Thermoset | 0.40 | |
| | Extruded | 0.27 | |
| | Other | 0.40 | |
| Glass | Float Glass | 0.20 | (Nippon Steel 2010; NSG Group 2010) |

### 4.11.8 Data Variability

As can be seen by reviewing each of the previous sections there is much variability in the data for the production of nonmetals. However, these values tend to stay within a particular magnitude for both water use and water consumption as shown in Figure 22 and Figure 23. Both figures show the average water values and also show the highest and lowest possible values based on the information presented. Even on the worst case scenario, the water consumption would still be smaller than that for the production of metal parts. If the producers of plastics did not recycle water, but rather choose to have a single pass cooling system, then perhaps its water use would be higher than that of metals, but its water consumption would remain relatively the same because of the evaporation rate associated with it.

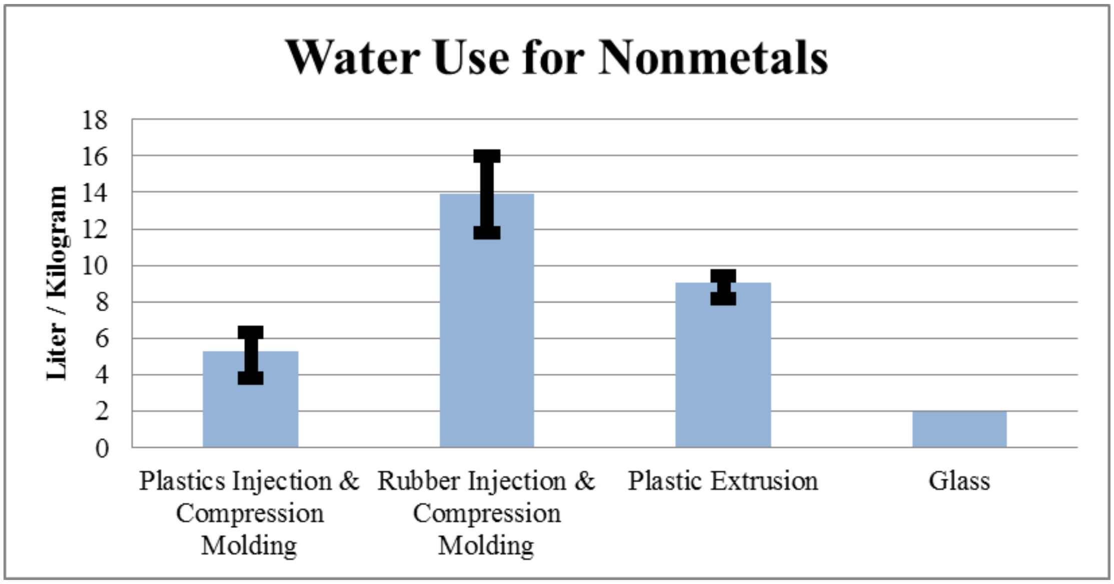

Figure 22: Water Use for Nonmetals Variability

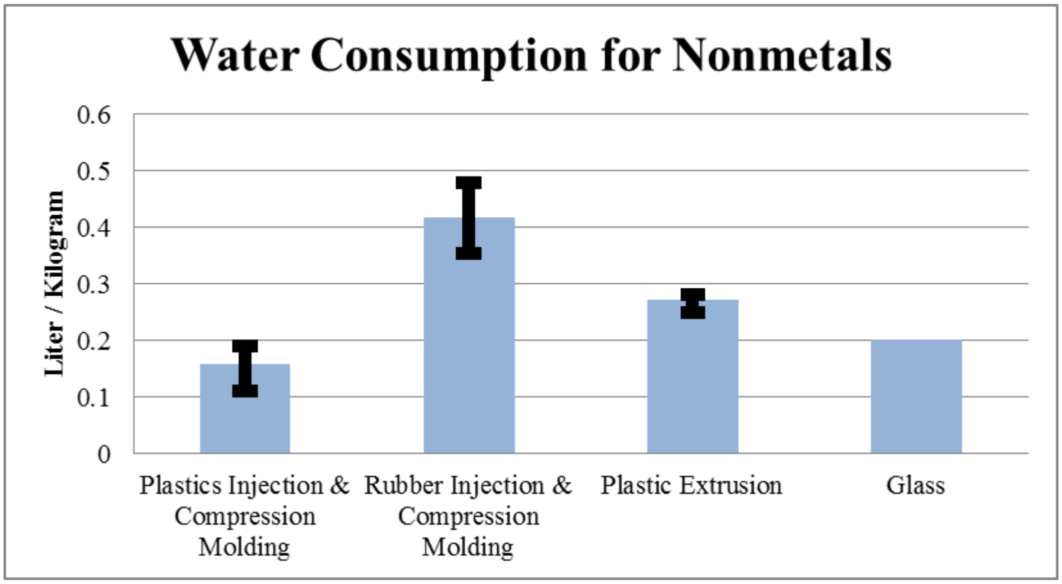

Figure 23: Water Consumption for Nonmetals Variability

## 4.12 Water Consumption for Parts Production

Based on the information presented in the previous sections, a summary table for water consumption in the production of parts can developed. Basically, by coupling the material composition from Table 22 with the water consumption from the process for metals shown in Figure 12 and the water consumption from the processes for nonmetals shown in Figure 13, an overall water consumption analysis can be created as shown in Table 42 and in Table 43. The total water consumption for the primary processes is 855 liters. The water consumption for the secondary processes is 47 liters. The total water consumption is then added to be 902 liters in the production of parts. As can be seen, much of the water is consumed in the casting of aluminum and steel, with aluminum having a higher impact even though its part in the material composition of the vehicle is much lower than steel, as shown in Figure 24. Although coolant is used in machining operations, much of it is either recycled or composed of oil instead of just water. More conservative values were used in terms of water composition of water evaporation. Assuming more wasteful numbers would result in higher water consumption values.

Table 42: Water Consumption Summary for Primary Processes

| Material | Weight (Kg) | Primary Process | Liters / Kg | Total Liters | |
|---|---|---|---|---|---|
| **Iron** | 194.82 | **Cast**<br>165.60 | 1.50 | 248.40 | 270.60 |
| | | **Forged**<br>29.22 | 0.76 | 22.21 | |
| **Steel** | 598.97 | **Stamped**<br>419.28 | 0.00 | 0.00 | 18.21 |
| | | **Forged**<br>23.96 | 0.76 | 18.21 | |
| **Aluminum** | 154.22 | **Cast**<br>117.21 | 3.80 | 445.39 | 472.35 |
| | | **Forged**<br>35.47 | 0.76 | 26.96 | |
| **Copper** | 20.41 | **Drawn**<br>13.88 | 0.01 | 0.17 | 3.37 |
| | | **Cast**<br>6.53 | 0.49 | 3.20 | |
| **Other Metals** | 7.26 | **Cast**<br>7.26 | 1.50 | 10.89 | 10.89 |
| **Rubber** | 60.33 | **Compression Molded**<br>53.69 | 0.42 | 22.55 | 25.34 |
| | | **Injection Molded**<br>6.64 | 0.42 | 2.79 | |
| **Plastics** | 181.44 | **Compression Molded**<br>23.59 | 0.16 | 3.77 | 45.72 |
| | | **Injection Molded**<br>72.58 | 0.16 | 11.61 | |
| | | **Thermoset**<br>48.99 | 0.40 | 19.60 | |
| | | **Extruded**<br>29.03 | 0.27 | 7.84 | |
| | | **Other**<br>7.26 | 0.40 | 2.90 | |
| **Glass** | 39.92 | **Float Glass**<br>39.92 | 0.20 | 7.98 | 7.98 |
| **Total** | 1257.37 | | | **854.46** | |

Table 43: Water Consumption Summary for Secondary Processes

| **Material** | **Weight (Kg)** | **Primary Process** | **Secondary Process** | **Liters / Kg** | **Total Liters** |
|---|---|---|---|---|---|
| **Iron** | 194.82 | **Cast**<br>165.60 | **Machined**<br>158.97 | 0.00 | 0.00 |
| | | **Forged**<br>29.22 | **Machined**<br>29.22 | 0.00 | 0.00 |
| **Steel** | 598.97 | **Stamped**<br>419.28 | **Machined**<br>25.16 | 0.40 | 10.06 |
| | | **Forged**<br>23.96 | **Machined**<br>14.85 | 0.40 | 5.94 |
| **Aluminum** | 154.22 | **Cast**<br>117.21 | **Machined**<br>107.83 | 0.28 | 30.19 |
| | | **Forged**<br>35.47 | **Machined**<br>1.06 | 0.28 | 0.30 |
| **Total** | 948.01 | | | | **46.50** |

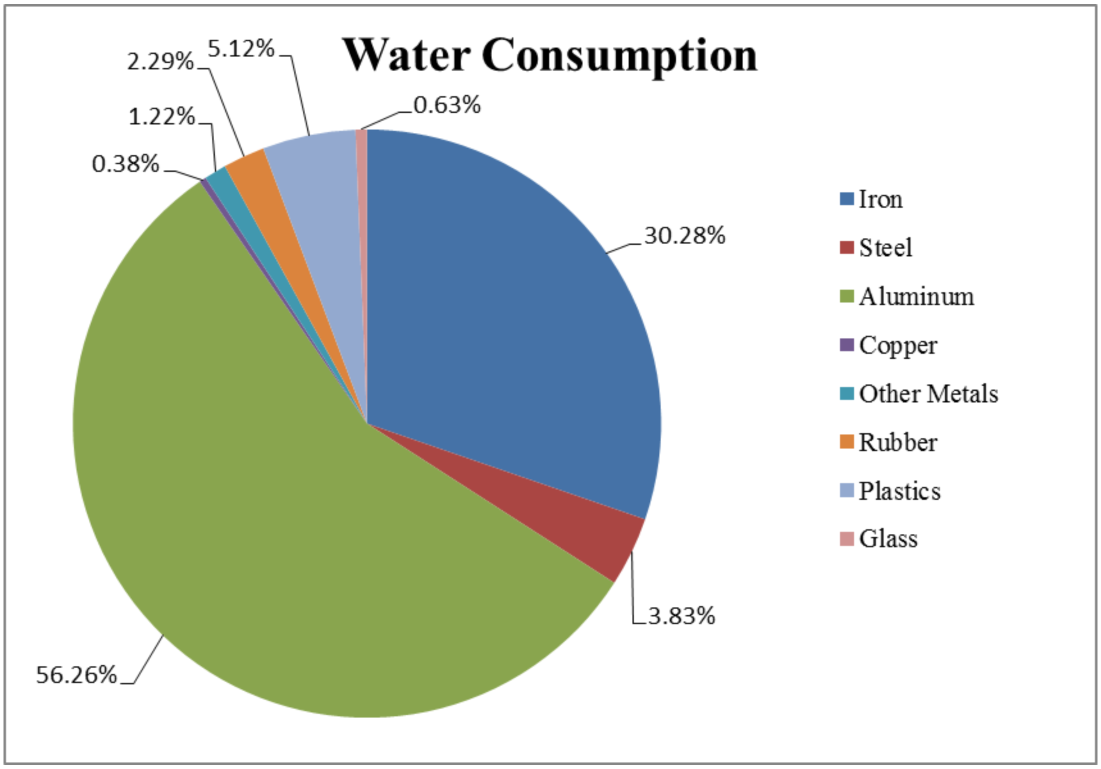

Figure 24: Water Consumption Percentages

## 4.13 Comparison of Water Consumption and Water Use

The comparison of the environmental impact in terms of the total water use and consumption between the EcoInvent data, and the analysis based on literature data found below in Figure 25. As can be seen, the EcoInvent data differs significantly from that obtained from the analysis. The EcoInvent data places a more even distribution along the metals, while the analysis data focuses in on the water consumption more on Aluminum, specifically, the casting of aluminum. The effect of steel is also much more significant based on the EcoInvent database. For this analysis, steel had a minimal effect because stamping played a very small role due to the lack of water consumption. However, EcoInvent may take into account water for cleaning, which this thesis did not include as explained in that section. In other words, using EcoInvent, even for just water intake in the production of parts for the life of a vehicle would be questionable because of their inconsistent scopes.

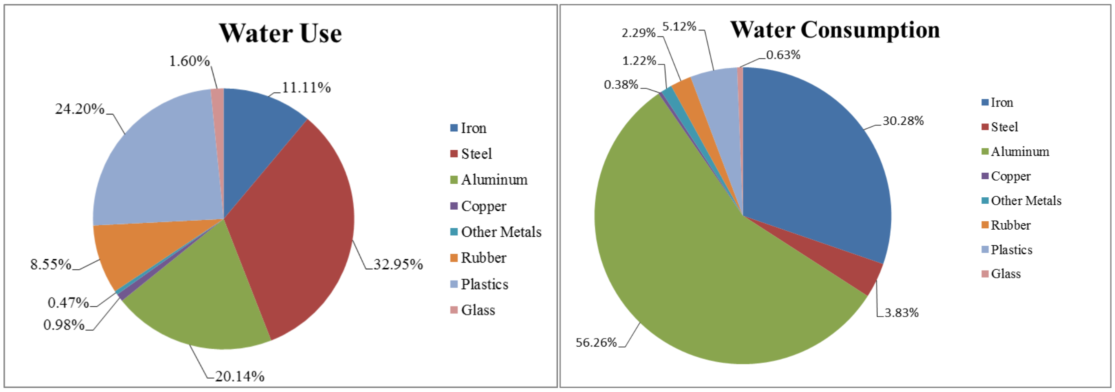

Figure 25: Water Comparisons (EcoInvent on Left, Literature Data on Right)

## 4.14 Additional Water Consumption Scenarios

The water consumption developed in the previous sections of this chapter tend to align with the best case scenarios where water composition values were lowest in machining and recycling rates were highest. The work of this thesis only took the lowest possible water consumption value for casting of aluminum. However, reversing this trend for these two values could potentially create a water consumption value which is up to twice that listed previously. Using the water consumption rate of 7.8 liters per kilogram for aluminum, and a 95 % water composition rate and 10 % evaporation rate for machining operations would yield a water consumption value of 1515.3 liters. Modifying any of other parameters for the production of parts would have a minimal, almost negligible impact on the overall water consumption.

The only other possible inclusion that could have a significant effect on the overall water requirements for the production of parts are stamping operations because it makes up approximately 33 % of the vehicle percent based on Table 42. However, no important record could be found for the water required for this operation. The only lubricants recommended were oil-based as explained in section 4.10.4.3 which also discussed the possibility of wastewater evaporation.

# CHAPTER 5:

# PRODUCTION AND ASSEMBLY

## 5.1 Scope

This chapter focuses on quantifying the water consumption in the production and assembly phase for a vehicle. This encompasses all steps necessary to assembly the parts, connect the assemblies together, and put the finishing touches required by the automakers to produce the final vehicle to be sold to the customer. This can include welding, painting, and general assembly. Depending on the level of manufacturing and outsourcing, some of the processes involved may overlap with those of the parts production and may also include other processes, like maintaining facilities that would not align with the goals for this analysis. An effort was made to differentiate amongst the two.

## 5.2 Data Sources

John Semmens, a graduate student in the mechanical engineering department and MBA candidate here at the Georgia Institute of Technology compiled much of the information presented in this chapter. It is because of his efforts that all of this data was organized as such.

All water data for this chapter was taken from various automakers most recent sustainability reports with the exception of Honda. As no report is available for Honda, data is taken from the company's Global Environmental Impact website available at (Honda 2011). These reports give water input data and, in some instances, water output. General Motors is not considered as no water data is obtainable for this company. Companies used for the water data, along with their reference, are given below in Table 44. In some instances, information had to be gathered from additional sources, like the company website or other reports publicly available from the automakers. In these cases, the sources will be explicitly provided to avoid confusion.

Data in this chapter is also categorized by the type of activity where water is used or consumed. Three classifications are typically reported including production, non-manufacturing, and company-wide water figures. The combination of a company's production and non-manufacturing water footprint is assumed to be equivalent to that OEM's company-wide water footprint. Thus knowing information about any two of a company's activities allowed the calculation of a third.

Table 44: OEM Sustainability Reports

| Company | References |
|---|---|
| BMW | (BMW 2010) |
| Chrysler | (Chrysler 2011) |
| Daimler | (Daimler 2010) |
| Ford | (Ford 2011) |
| Honda | (Honda 2011) |
| Hyundai | (Hyundai 2012) |
| Kia | (Kia 2011) |
| Mazda | (Mazda 2011) |
| Nissan | (Nissan 2011) |
| Toyota | (Toyota 2011) |
| Volkswagen | (Volkswagen) |

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## 5.3 Uncertainty

The reporting of water data by car manufacturers is inconsistent as many reporting methods are utilized by OEMs to convey usage and consumption data. Issues arise through different understandings of the words “consumption” and “usage” as well as the varied way in which data is presented (i.e. in $m^3$/vehicle or as total water input and discharged). Differences also arise in classification of data as it relates to activities like production, non-manufacturing, or company-wide. In general, the classification of either consumption or usage given by OEMs to their water data is maintained throughout this analysis. Exceptions to this practice are introduced for Honda, Mazda, and BMW whose classifications proved contradictory. For example, the table relating Honda’s production water data is titled “Manufacturing-related energy and water consumption, and waste by region” whereas the specific row header delineating the water figures is titled “Water use” (Honda 2011).

Such reporting issues are likely the result of linguistic translations from German and other languages to English because use and consumption are often used as synonyms in dictionaries and thesauri. With this understanding, additional consumption data analyzed as such in this chapter could become suspect. Daimler and Toyota in particular report high consumption values which may in fact reflect usage.

The chapter will attempt to differentiate between the two types and create a set of data points which are consistent with the said definitions from section 1.4 for comparison with other stages in the life of a vehicle.

## 5.4 Reported Water per Vehicle

BMW, Daimler, Ford, Kia, Toyota, and Volkswagen directly report water use or water consumption on a per vehicle basis in their sustainability reports. These values are provided in Table 45 and are categorized according to activity (i.e. production, non-manufacturing, or company-wide data). Based on this data, only Volkswagen’s water consumption is a derived value. This company directly reports per unit water usage as 5.01 $m^3$/vehicle, however, it also provides a per unit wastewater figure of 3.82 $m^3$/vehicle. Thus Volkswagen's production water consumption is taken to be the difference of these two values or 1.19 $m^3$/vehicle (Volkswagen 2011).

Table 45: Directly Reported per Unit Water Usage

| Company | Usage (m^3/ vehicle) | Consumption (m^3/ vehicle) | Activity |
|---|---|---|---|
| BMW | 2.31 | N/A | Production |
| Daimler | N/A | 6 | Production |
| Ford | 4.8 | N/A | Production |
| Kia | N/A | 4.9 | Company |
| Toyota | N/A | 3.7 | Company |
| Volkswagen | 5.01 | 1.19 | Production |

## 5.5 Reported Water Data

BMW, Chrysler, Honda, Hyundai, Mazda, and Nissan similarly report water inputs and wastewater discharges for their 2010 activities. These inputs and outputs, as well as whether each figure is stated to be from production or a combination of production and non-manufacturing activities, are provided in Table 46. If both an input and discharge figures are available, the difference, water input minus wastewater discharge, is calculated to represent a manufacturer's water consumption. Alternatively, Daimler, which did not indicate water inputs and discharges, did report production water consumption of 12,000,000 $m^3$ (Daimler 2010).

Table 46: Reported Water Inputs and Wastewater Discharges

| Company | Water Input (m^3) | Water Discharge (m^3) | Water Consumption (m^3) | Activity |
|---|---|---|---|---|
| BMW | 3,418,816 | 2,427,754 | 991,062 | Production |
| Chrysler | 10,684,609 | 7,057,625 | 3,626,984 | Company |
| Daimler | N/A | N/A | 12,000,000 | Production |
| Honda | 29,148,000 | N/A | N/A | Production |
|  | 33,300,000 | N/A | N/A | Company |
| Hyundai | 19,622,000 | N/A | N/A | Company |
| Mazda | 15,269,000 | 7,607,000 | 7,662,000 | Company |
| Nissan | 25,851,000 | 19,784,000 | 6,067,000 | Production |

## 5.6 Vehicle Production

The OEM’s respective 2010 vehicle production values are given in Table 47. These data points are the number vehicles each company produced for that particular year. This information is to be used when calculating the water use and water consumption on a per vehicle basis. Some of the sources used in this section are the same as the sources used to determine the water input. However, in some instances, the sources did not include vehicle production so additional automaker references were found which could either be other reports or articles from their websites. Only vehicles that seemed to fit the particular specification set forth in section 5.4 were included. In other words, trucks were not included or any other large vehicles that would be different. Additionally, only data from a worldwide company dataset rather than focusing on a particular area outside of the U.S was selected. In other words, if they company sold cars in the U.S., it was included, but if the data reported was exclusively for another country, it was excluded. This was done in an attempt to better remain in scope concerning the type and size of vehicle seven if the water and vehicle production data from automakers may include the production of cars outside of the U.S. in their reports.

Table 47: 2010 production figures by OEM

| Company | 2010 Number of Vehicles Produced | Reference |
|---|---|---|
| BMW | 1,481,253 | (BMW 2010) |
| Chrysler | 1,571,662 | (Chrysler 2011) |
| Daimler | 1,936,981 | (Daimler 2011) |
| Ford | 5,351,000 | (Ford 2011) |
| Honda | 3,642,000 | (Honda 2011) |
| Hyundai | 626,151 | (Hyundai 2011) |
| Kia | 2,138,802 | (Kia 2011) |
| Mazda | 1,307,540 | (Mazda 2011) |
| Nissan | 4,053,701 | (Nissan 2011) |
| Toyota | 8,557,351 | (Toyota 2011) |
| Volkswagen | 7,357,505 | (Volkswagen) |

## 5.7 Calculated Water Requirements per Vehicle

The water usage per vehicle is calculated by dividing the total water input by the total number of vehicles produced. In other words, divide the water input from Table 46 by the vehicle production from Table 47. The water consumption per vehicle is calculated by dividing the total water consumption by the number of vehicles produced. In other words, divide the water consumption from Table 46 by the vehicle production from Table 47. The results of these calculations can be found in Table 48. The display is organized by water consumption from lowest to highest. Those companies without consumption data are grouped by water usage at the bottom of the table from lowest to highest.

The results for the eleven OEMs as given vary widely in terms of both water usage and consumption. BMW had the lowest calculated usage and consumption values of 2.31 $m^3$ per vehicle and 0.67 $m^3$ per vehicle respectively. Mazda had the highest calculated usage at 11.68 $m^3$/vehicle and Daimler the highest consumption at 6.20 $m^3$ per vehicle. As can be seen, there is much variability in the calculated data. BMW's water use is less than one fourth that of Mazda. This could be explained by three possible differences in their reported data. First, it could be that BMW outsources more of the production operations and thus uses less water directly. In other words, they could be pushing their water use towards their supply chain while minimizing in house operations. Secondly, BMW could simply be reporting more direct operations rather than including things like facility maintenance which would account for a broader set of water data. And lastly, BMW could simply be using the latest technology and actively recycling and reusing water which would mean that water inputs into their facilities are much less than those of Mazda. It is likely that the results shown in Table 48 for water use and water consumption on a per vehicle basis for the different automakers vary as a result of these three possibilities on supply chain, scope, and internal practices. In other words, some variance is due to different approaches for reporting water data in sustainability reports. There is no set standard for whether OEMs report water data on a per unit basis or in terms of input and output flows. There are also differences inherent in the reported production, non-manufacturing, or company-wide activities which can add water used and consumed in office buildings, research centers, or other non-assembly related activities.

Table 48: Non-manufacturing water usage/consumption

| Company | Per Unit Usage (m^3/vehicle) | Per Unit Consumption (m^3/vehicle) | Activity |
|---|---|---|---|
| BMW | 2.31* | 0.67 | Production |
| Nissan | 6.38 | 1.5 | Production |
| Chrysler | 6.44 | N/A | Production |
|  | 0.36 | N/A | Non-production |
|  | 6.8 | 2.31 | Company |
| Toyota | N/A | 3.70* | Company |
| Kia | N/A | 4.90* | Company |
| Mazda | 11.68 | 5.86 | Company |
| Daimler | N/A | 6.2 | Production |
| Ford | 4.80* | N/A | Production |
| Volkswagen | 5.01* | 1.19 | Production |
| Hyundai | 5.41 | N/A | Company |
| Honda | 8 | N/A | Production |
|  | 1.14 | N/A | Nonproduction |
|  | 9.14 | N/A | Company |

*Indicates a directly reported per unit value in m3/vehicle as given by

### 5.8 Non-Manufacturing Water Requirements

In an attempt to clarify this last point, non-manufacturing water usage/consumption is isolated where possible from an OEM's reported water data. Only two manufacturers (Honda and Chrysler) provide enough information to analyze this aspect. Honda provides both company-wide and production specific water usage data which allows calculation of their non-production related water usage as the difference between these two. Chrysler reports a non-manufacturing discharge to public sewers of 561,188 m^3 (Chrysler 2011).Though Chrysler's non-manufacturing discharge neglects any water lost through consumption, this loss is assumed to be small such that the 561,188 m^3 approximates total non-manufacturing water usage.

These non-manufacturing water usages/consumptions are presented as reported and on a calculated per unit basis. Even with the assumption made about Honda's non-manufacturing discharge, this company's per unit usage (0.36 m^3 per vehicle) below the Honda's usage (1.14 m^3 per vehicle). Thus while use of 0.36 m^3 per vehicle does not account for Chrysler's total non-manufacturing water usage, it is reasonable to suggest that the real number falls somewhere below Honda's 1.14 m^3 per vehicle. Thus in Table 49 Chrysler's production specific water usage (6.44 m^3 per vehicle) is determined as the difference between the reported company-wide water usage (6.80 m^3 per vehicle) and the estimated non-manufacturing (0.36 m^3 per vehicle) water usage.

For U.S. auto manufacturers, Ford had lower production water usage than Chrysler, at 4.80 m^3 per vehicle, compared to an estimated 6.44 m^3 per vehicle respectively. Water consumption figures for Ford are unavailable, while Chrysler reports company-wide water consumption of 2.31 m^3 per vehicle. General Motors did not provide and water usage or consumption information.

Table 49: Non-manufacturing water usage/consumption

| **Company** | **Non-manufacturing Water (m^3)** | **Per Unit (m^3 vehicle)** | **Usage / Consumption** |
|---|---|---|---|
| Chrysler | 561,188 | 0.36 | Usage Discharge |
| Honda | 4,152,000 | 1.14 | Usage |

### 5.9 Discrepancies

Similarly, Mazda reports a company-wide water consumption of 15,269,000 m^ 3 and a wastewater discharge of 7,607,000 m^3 (Mazda 2011). It seems unlikely that the company's consumption is greater than its total water discharge, especially since this is not the case for any other OEM examined. Thus 15,269,000 m^3 is maintained as a usage value.

BMW reports 2.31 m^3 per /vehicle as a per unit water consumption value in their sustainability report, but this figure is also maintained as a usage value here (BMW 2010). The difference becomes evident when analyzing BMW's reported water input of

3,418,816 m$^3$. (BMW 2010). By dividing input by a 2010 production of 1,481,253 vehicles, a per unit usage figure of 2.31 m^3 per vehicle is achieved (BMW 2010).

A final discrepancy is found when comparing reported water data in Toyota's 2010 and 2011 sustainability report (Toyota 2011). Toyota lists 2009 water consumption as 4.4 m^3 per vehicle. In their sustainability report of 2009, Toyota lists the water consumption as 3.6 m^3 per vehicle (Toyota 2010). This example further illustrates some of the inconsistencies present when analyzing water data from OEM sustainability reports.

## 5.10 Conclusion

The results from Table 48 are also presented in Figure 26 and Figure 27 categorized by usage and consumption respectively. Each figure maintains the distinction between production and non-manufacturing activities where applicable or company-wide figures if not. A comparison of the two shows that water usage is generally far greater on a per vehicle basis than water consumption. This is to be expected. Additionally, the available non-manufacturing information indicates that water used in these activities (i.e. office buildings, research labs, etc.) is generally negligible when compared to water used in production. Chrysler's water usage discharge and Honda's non-manufacturing water use represent 6% and 14% of their respective production water usages. Yet while non-manufacturing water use/consumption may be small, finding ways to mitigate water usage for non-manufacturing activities could still have a real impact on auto manufacturers' water footprints.

To calculate the total water consumption in the life of a vehicle, the value 0.67 m^3 per vehicle (670 liters per vehicle) will be selected because it represents the best case scenario. For most of my analysis, the best case scenario is assumed, so selecting this value would be consistent with the scope for the other phases. However, it can be seen that the water consumption could be as much as much as 2.31 m^3 per vehicle (2310 liters per vehicle) if the Chrysler data points were to be used.

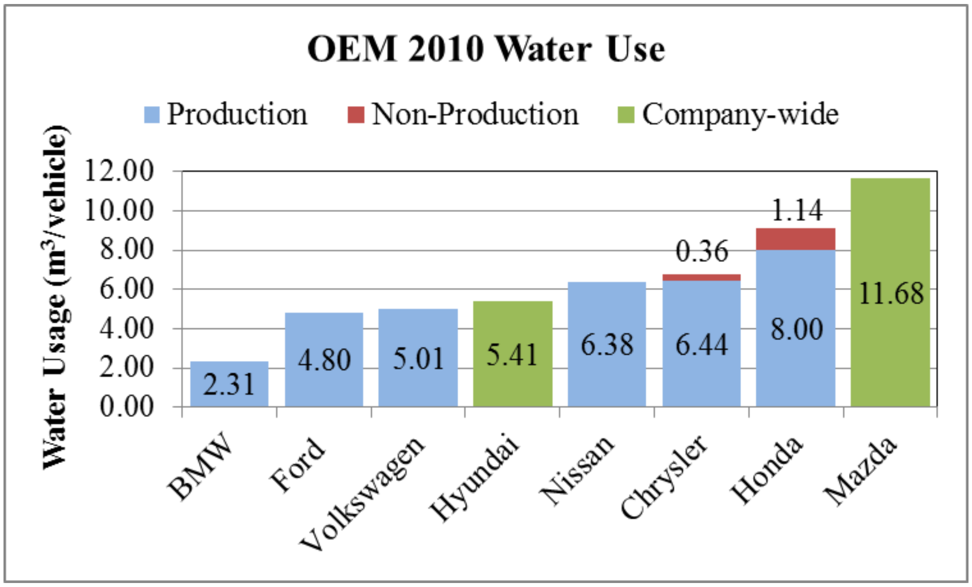


Figure 26: Water use by OEM on a per unit basis in 2010

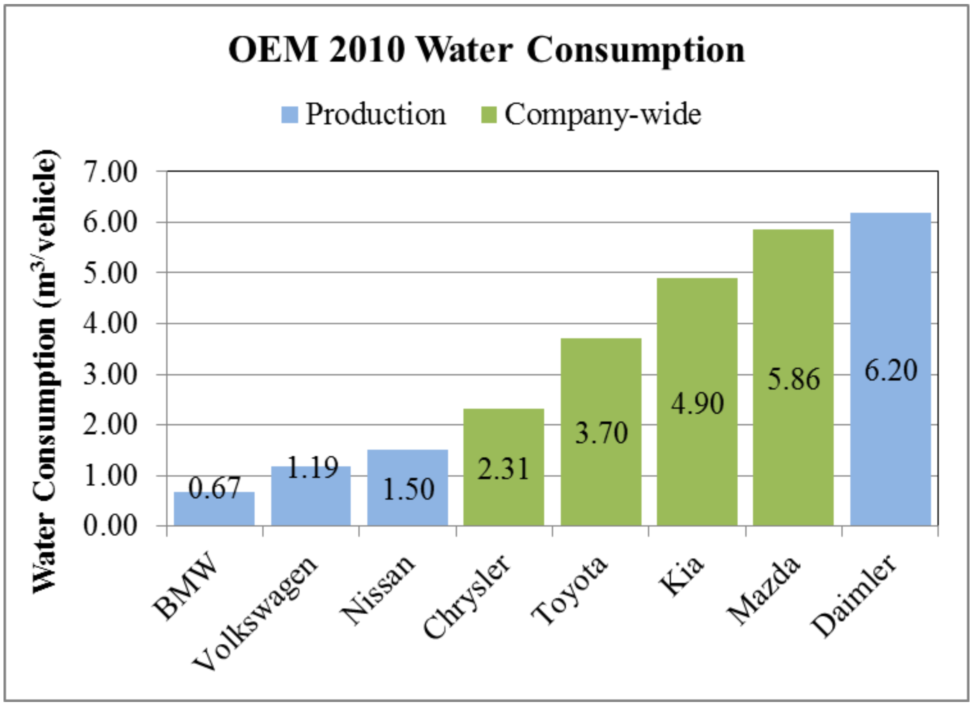


Figure 27: Water consumption by OEM on a per unit basis in 2010

# CHAPTER 6:

# USE PHASE

## 6.1 Scope & Methodology

The assessment in the use phase stage will only include water consumed for the production of fuels used during the life of a vehicle under normal driving conditions. It is assumed that the fuel is to be extracted from the earth, requires processing, and that it is to be transported from where it is produced to where it will be consumed. This assessment will not include other maintenance water inputs for a vehicle such as washing, cleaning, oil changes, etc. There would be too much variability on this data and would probably mostly include water use rather than water consumption. Water for maintenance would also potentially include facilities requirements rather than direct water consumption, which is not consistent with the scope of this thesis. This chapter will strictly focus on fuel consumption for a specific set of driving conditions as shown below in Figure 28; these conditions to be explained in later sections. However, different parameters will vary to demonstrate the effects that different assumptions would have on the overall water consumption

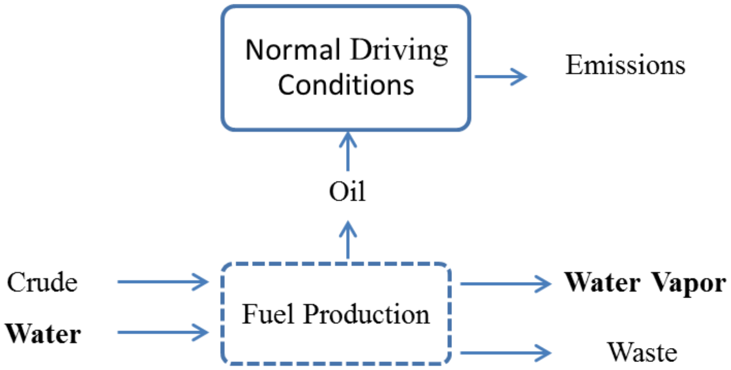


Figure 28: Scope of Analysis

To calculate the total water consumption, an appropriate total driving distance experience by an average vehicle during its life was used. This distance was then divided by the fuel efficiency based on the current Corporate Average Fuel Economy standard to determine the amount of fuel consumed. This value was multiplied with the water consumed for the production the fuel on a liter per liter basis to calculate the total water consumption. Different variability studies will demonstrate the influence these parameters have on the use phase, which will be shown to have the greatest impact in the on the overall water consumption. Finally, the work of this thesis gathered water use data from EcoInvent for comparison.

## 6.2 Data Sources

An effort was made to ensure that the data used was from sources that were either tied to industry, published in an academic journal, or from obtained  a government agency and that the definitions for water use and water consumption on said data were consistent with those of the thesis. Three main sources were used to calculate the water consumption for the use phase.

First, a recently submitted that provided a basis for much of the data was used. It referenced the most up to date papers on the matter that contained existing analyses on water consumption for fuel production (Yen 2011). This subject has been examined previously in depth, so there was plenty of data available. Said thesis also described the fuel production steps and the factors influence it. (Gleick 1994; Wu, Mintz et al. 2009; Harto, Meyers et al. 2010; Yen 2011).

Secondly, information was obtained from a government report published by the Department of Energy and the Environmental Protection Agency for the fuel efficiency data. This report gave the minimum required fuel efficiency for a vehicle to be manufactured as well the fuel efficiencies for a number of other vehicles which were used in the variability studies (U.S. Environmental Protection Agency 2012).

Thirdly, previous studies examining the life of a vehicle were used in order to determine an appropriate lifetime driving distance for a vehicle. These studies gave different parameters based on previous work to better understand how much a car is actually driven (Sullivan and Cobas-Flores 2001; Nemry, Leduc et al. 2008).

And finally, data from EcoInvent was compiled on the water inputs for fuel productions. This water use data was compared to the water consumption to better establish how recycling of water significantly reduces the overall water splash.

## 6.3 Fuel Production Literature Review

The first major life cycle water assessment for petroleum-based fuels was conducted as part of the comprehensive energy-water outlook as described (Gleick 1994), where Gleick assessed water demands for the extraction and refining processes for crude oil and petroleum. Water consumption was calculated for onshore exploration and primary extraction, for secondary and tertiary methods including enhanced oil recovery (EOR) technologies, as well as for petroleum refining. While water consumption data for petroleum extraction and refinement in (Gleick 1994) illustrate the widely varying water requirements for producing gasoline, there is no information regarding the distribution of these technologies in fuel production pathways in the United States (Yen 2011).

A more recent study provides a more detailed breakdown of available fuel extraction technologies based on the process water flows, as shown in Figure 29, from which a weighted average of primary and additional oil extraction water consumption could be determined (and by extension a comprehensive range of total water consumption for gasoline production) (Wu, Mintz et al. 2009). The study outlines the technology shares in onshore and offshore crude oil extraction in key production regions in the United States, as shown in Figure 30. The authors considered three major petroleum-producing regions in the United States that contribute to 90 percent of domestic crude oil production and 81 percent of oil refining (Yen 2011).

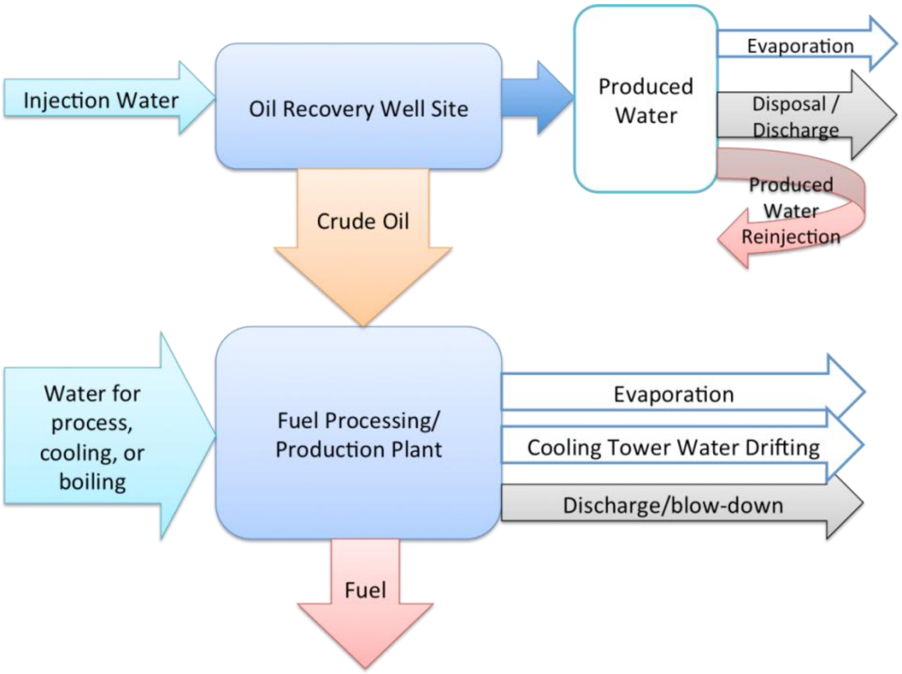


Figure 29: Water Inputs and Outputs for Petroleum Production (Wu, Mintz et al. 2009; Yen 2011)

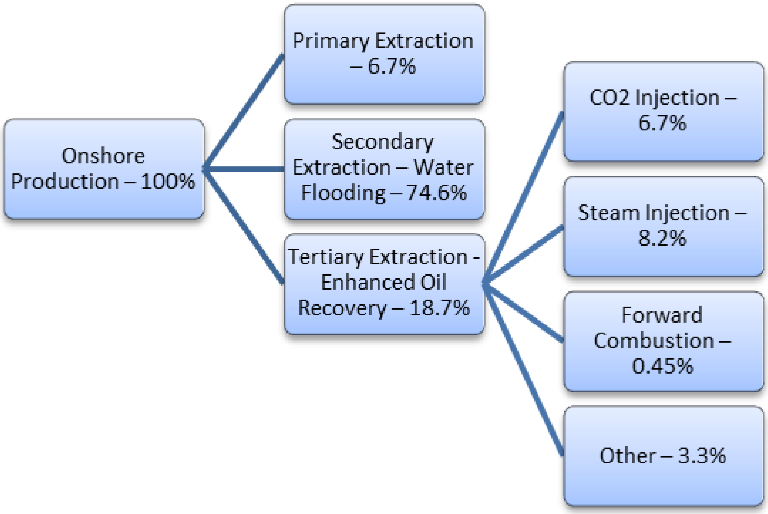


Figure 30: Technology Distribution for Onshore Oil Production (Wu, Mintz et al. 2009; Yen 2011)

In addition to specifying the distribution of primary and secondary oil recovery technologies in these regions, the researchers also examine the amount of produced water stemming from water stored in extracted crude oil that needs to be removed from the extracted fuel; some of the produced water is reintroduced to the well via water flooding and injection in secondary recovery methods. This is combined with the above refining water consumption range stated in the previous study to obtain an aggregate range of 5.4 to 7 liters of water per liter of gasoline (Yen 2011).

The authors also considered foreign oil production by examining water consumption trends in Saudi Arabian oil production, as that region has a lack of surface water and low recharging aquifer rates (Wu, Mintz et al. 2009; Yen 2011). Much of the water used in the oil production process in Saudi Arabia is treated from brackish or seawater resources and the authors stress that water consumption values are based on individual wells and projects instead of a national distribution. Similarly, the authors considered petroleum recovered from Canadian oil sands, which accounts for 39 percent of total petroleum production in Canada. To produce oil from oil sands, bitumen is either extracted from surface mining or by using in situ extraction methods and is processed into synthetic crude oil; it is then processed into synthetic crude oil. As with EOR technologies for conventional crude extraction, the authors assessed water demands based on a national technology distribution for oil sands production. Water consumption for oil sands crude production was leveraged from Gleick's study (which includes a brief assessment of oil sands crude production) and later assessments for surface mining and in situ oil sands extraction. In addition to specifying the distribution of primary and secondary oil recovery technologies in these regions, the researchers also examined the amount of produced water stemming from the removal water stored in the extracted crude oil; some of the produced water is reintroduced to the well via water flooding and injection in secondary recovery methods (Yen 2011).

These water consumption values are summarized below in Figure 31, where a direct comparison shows that water consumption varies significantly based on regional conditions for conventional crude extraction, while water consumption in Saudi Arabian and Canadian oil sands production are slightly lower overall.

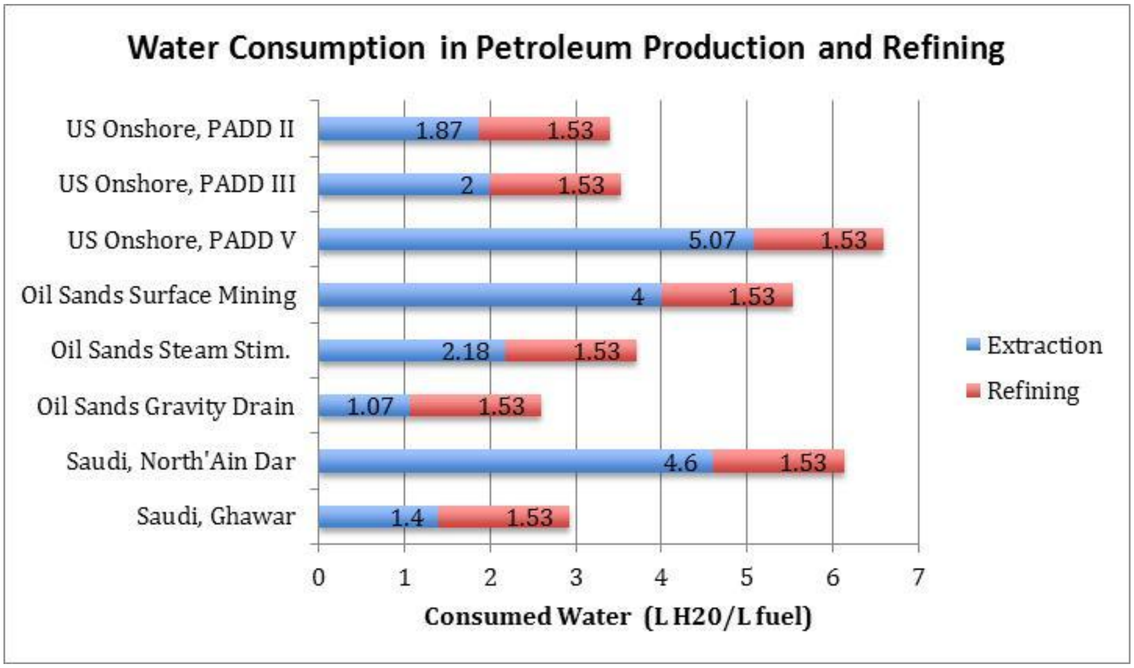


Figure 31: Water Consumption for Petroleum Production and Refining for U.S., Canadian, and Saudi Production (Wu, Mintz et al. 2009; Yen 2011)

A final study examined the distribution and marketing associated with fuel consumption. The authors estimated water consumption to be between 0.7 and 2.7 liters of water per liter of gasoline. The unexpectedly high value for distribution and marketing can be attributed to water consumption related to running fuel pipelines. Most fuels are not extracted or produced in close proximity to the demand, so large amounts of resources are also attributed to transporting them to these locations (Harto, Meyers et al. 2010).

Table 50 below summarizes the water consumption data for the production of fuels based on the different sources. It includes extraction, production, and transportation for different technologies and for different technologies. As can be seen there is much variability on the data depending on where it was obtained, the kind of technology being used, and the application. Some of the values were obtained using process-level data on water use (by fuel production technology) from the literature and weighted them by estimated market share to derive averages. The authors also identified variations among regions, characterized them according to a range of data values, and (in the case of relatively large variations) reexamined them to identify responsible factors (Wu, Mintz et al. 2009). Table 51 is the aggregate estimate for the three main processes. It lists the low, the high, and the average value for each. The average aggregate value for extraction and refining was given in the sources based on their weighted calculations, while the value for transportation was simply calculated based on the average of the low and the high water consumption numbers. These aggregates values are to be used in future calculations. A variability study will show how they can affect the overall water consumption (Wu, Mintz et al. 2009). For future calculations, it is assumed that 3.8 liters of water are consumed for each liter of fuel produced. This would represent the best case scenario. Future variability analysis will show the effect of selected a different combination for fuel production water consumption.

Table 50: Water Consumption for U.S. Onshore Petroleum Production

| Process | Sub-Process | Technology | Water Consumed (low), l/l | Water Consumed (high), l/l | Average Water Consumed, l/l | Reference |
|---|---|---|---|---|---|---|
| Extraction | Primary Recovery | | 0.1044 | 0.2784 | 0.21 | (Gleick 1994) |
| | Secondary Recovery | Water Flooding | | | 20.88 | |
| | | | Note: Based on 80 secondary oil wells | | 8.6 | (Wu, Mintz et al. 2009) |
| | | CO2 | | | 24.7 | (Gleick 1994) |
| | | | Note: Based on survey of 14 oil companies | | 13 | (Wu, Mintz et al. 2009) |
| | | Shell CO2 Project, Denver | | | 4.3 | |
| | Enhanced Oil Recovery | Average | | | 4.176 | (Gleick 1994) |
| | | Thermal injection | 3.48 | 6.264 | | |
| | | Air Injection | | | 1.74 | |
| | | Micellar Polymer | | | 309.72 | |
| | | Caustic Injection | | | 3.48 | |
| | | Average for CO2, Steam, Combustion | | | 8.7 | (Wu, Mintz et al. 2009) |
| | | Weighted Average | Note: Based on technology shares in U.S. for 2008 | | 8 | |
| | | Produced Water | Note: 71% of Produced Water is Reinjected | | -6.8 | |
| | | Net Water Consumed | Subtract (0.71*Produced Water) from Weighted Average | | 3.2 | |
| Refining | | Traditional | 1 | 2.5 | | (Gleick 1994) |
| | | Reforming | 2.088 | 4.176 | | |
| | Aggregate | | 1 | 1.85 | 1.53 | (Wu, Mintz et al. 2009) |
| | Survey Range | | 0.5 | 2.5 | | |
| Transport | Aggregate | | 0.65 | 2.7 | 1.3 | (Harto, Meyers et al. 2010) |
| Extraction | | | 2.1 | 5.4 | | (Wu, Mintz et al. 2009) |

Table 51: Water Consumption for Production of Gasoline

| **Process** | **Water Consumed (low), l/l** | **Water Consumed (high), l/l** | **Water Consumed (Average), l/l** | **Reference** |
|---|---|---|---|---|
| Refining | 1.0 | 1.9 | 1.5 | (Wu, Mintz et al. 2009) |
| Transport | 0.7 | 2.7 | 1.3 | (Harto, Meyers et al. 2010) |
| Extraction | 2.1 | 5.4 | 3.7 | (Wu, Mintz et al. 2009) |
| **Total** | **3.8** | **10.0** | **6.6** | |

## 6.4 Corporate Average Fuel Economy

Corporate Average Fuel Economy (CAFE) is the sales weighted average fuel economy, expressed in miles per gallon (mpg), of a manufacturer's fleet of passenger cars or light trucks with a gross vehicle weight rating (GVWR) of 8,500 lbs. or less, manufactured for sale in the United States, for any given model year. Fuel economy is defined as the average mileage traveled by an automobile per gallon of gasoline (or equivalent amount of other fuel) consumed as measured in accordance with the testing and evaluation protocol set forth by the Environmental Protection Agency (EPA).

The minimum standard fuel economy as of 2011 is 27.5 miles per gallon or 11.7 km/liter of gasoline for CAFE (U.S. Environmental Protection Agency 2012). This value will be used as a basis for fuel efficiency although many other factors, like aggressive driving, excessive idling, weather conditions, loads, and improperly maintained engines can significantly affect the overall performance and thus reduce fuel efficiency (U.S. Environmental Protection Agency 2012). For a future section, different vehicles having different fuel efficiencies will be examined to better demonstrate the effects it can have on the water consumption in the use phase.

## 6.5 Lifetime Distance Miles

To determine the use phase water consumption it is necessary to calculate not only the fuel production water consumption and the vehicle fuel efficiency but also the total driving distance. There is much variability for this number; some vehicles may last upwards of 200,000 miles with intense maintenance while others may be destroyed after 10,000 miles. The total driving distance was calculated using two approaches. Government reports were reviewed to determine average existing data on the matter. Secondly, previous life cycle analyses were reviewed to see what numbers were being use for the lifetime distance miles.

A report written by the European Commission Joint Research Center was located which examined the effects a vehicle focusing on abiotic depletion, global warming, ozone depletion, photochemical pollution, primary energy, acidication, eutrophication, particulates, and solid waste. The study had a specific section which examined the effect of use phase for the life of a vehicle in comparison to other aspects. According to their sources, the average life of a gasoline car is 12.5 years; such a car travels a distance of 16,900 kilometers per year for a total driving distance of 211,250 kilometers, or approximately 132,000 miles (Nemry, Leduc et al. 2008). Although this data is based on European vehicles, it shows a reasonable magnitude and expected value for U.S. vehicles.

In addition to the government report, the data for the lifetime distance driven was located based on the paper summarizing previous work on life cycle analysis for vehicle up that point. The distances can be found below in Table 52. The data from the Golf A4 1.4 report was included as an additional data point. As can be seen the average distance driven is about 160,000 kilometers or 100,000 miles (Schweimer and Levin 2000; Sullivan and Cobas-Flores 2001). However, one downside to this data is that most it comes from older sources, so the expected lifetime distance driven by a vehicle today, due to improvements in technology, is probably closer to that presented in the European government report or as seen by the highest values from the paper (Nemry, Leduc et al. 2008).

Table 52: Lifetime Distance (Schweimer and Levin 2000; Sullivan and Cobas-Flores 2001)

| Study | Miles Driven | Kilometers | Source |
|---|---|---|---|
| Spark Ignited (1-A)* | 120,000 | 192,000 | (Sullivan and Cobas-Flores 2001) |
| Spark Ignited (1B)* | 120,000 | 192,000 | |
| Spark Ignited (2)* | 93,200 | 149,120 | |
| Spark Ignited (3)* | 58,500 | 93,600 | |
| Spark Ignited (5)* | 120,000 | 192,000 | |
| Spark Ignited (7)* | 99,000 | 158,400 | |
| Golf A4 1.4 | --- | 150,000 | (Schweimer and Levin 2000) |
| **Average** | | 161,017 | |

*In the article, SI denoted spark ignited. The number in the parenthesis is the study case.

For the use phase of a vehicle, the thesis will utilize the 100,000 mile (approximately 160,000 km) distance for the calculations because it is a number that can be used easily to scale the water consumption up or down. However, the thesis will also calculate the water consumption based on the 120,000 mile (approximately 193,000 km) value to demonstrate how selecting this distance would affect water consumption.

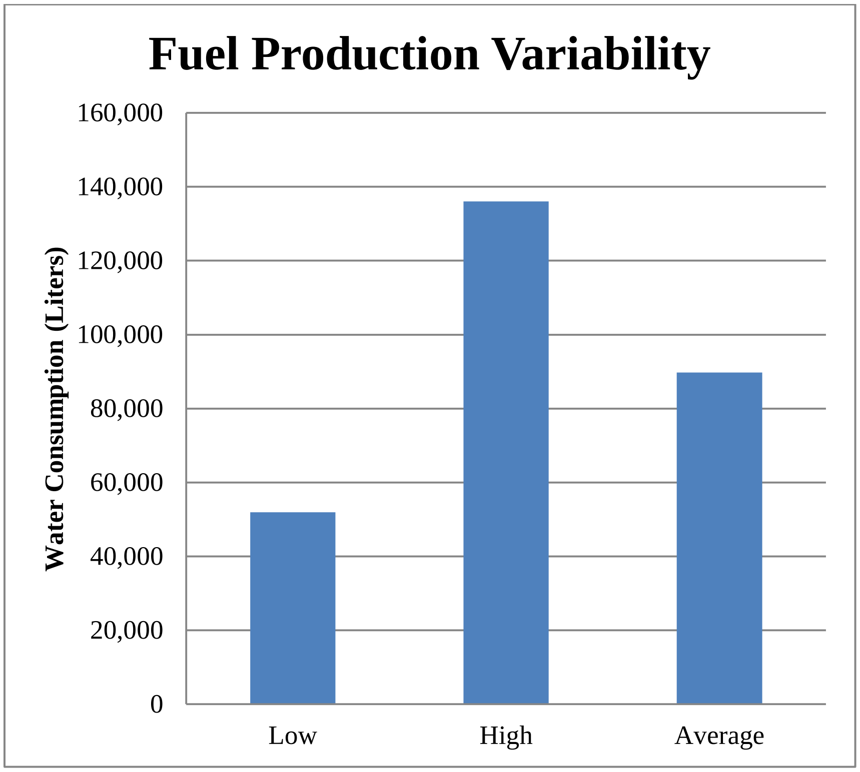
### 6.6 Use Phase Water Consumption Calculation

The assumptions used to calculate the water consumption for the use phase of a vehicle are as follow: 100,000 miles (160,000 km), fuel CAFE fuel consumption of 11.7 km / liter of gasoline, and 3.8 liters of water consumption per liter of fuel production. Driving this distance with said fuel efficiency would consume 13,675 liters of gasoline and thus 51,965 liters of water. Based on this number, the use phase for the life of a vehicle can be shown to have the biggest impact on the overall water consumption for the life of a vehicle. Using a driving distance of 120,000 miles (approximately 193,000 km), with the same fuel efficiency of 11.7, would consume 16,496 liters of gasoline or 62,693. Basically, the use phase, according to said parameters, consumes 0.52 liters of water per mile driven (or 0.33 liters per kilometer).

## 6.7 Fuel Consumption Variability

The initial assessment is calculated using the lowest values for fuel production consumption. However, there are other possibilities that must be examined to better understand the effect of these values in the overall water consumption. The other water consumption values can be calculated using the data from Table 51. Figure 32 shows the total water consumption using the low, average, and high values for fuel production water consumption. The same approach was used to calculate these values as explained earlier in section 6.6.

Figure 32: Fuel Production Variability (U.S. Environmental Protection Agency 2012)



## 6.8 Fuel Efficiency Variability

In addition to using different values for fuel production water consumption, another variable that can have an effect on the overall water consumption for the use phase is the vehicle fuel efficiency. A wide range of vehicle of different sizes having different fuel efficiencies were selected from a report written by the U.S. department of Energy having. The report uses estimates for all vehicles based on laboratory testing under standardized conditions to allow for fair comparisons. They try to create a general picture for each vehicle under three conditions: city, highway, and combined. A "city" estimate represents urban driving, in which a vehicle is started in the morning (after being parked all night) and driven in stop-and-go traffic. A "highway" estimate represents a mixture of rural and interstate highway driving in a warmed-up vehicle, typical of longer trips in free-flowing traffic. A "combined" estimate represents a combination of city driving (55%) and highway driving (45%) (U.S. Environmental Protection Agency 2012). A compilation of “combined” fuel efficiencies for different small to mid-size vehicles of 2012 along with the resulting water consumptions associated with each can be found below in Table 53. These water consumptions values were calculated using the same method described earlier in section 6.6. As can be seen, more fuel efficient vehicles have lower water consumption than less fuel efficient vehicles. Although the water consumption values do differ, as shown in Figure 33, their overall variability is minimal compared to the effects of changing the water consumption for fuel production as shown in section 6.7. That is not to say that vehicle efficiency should not be considered in determining overall water consumption. For older vehicles, which generally have much lower fuel efficiency, the use phase will have a high value for water consumption for the life of a vehicle. It should be noted, however, that, as technology to improve fuel efficiency is likely to continue to increase, water recycling technologies will continue to improve as well. So, the overall percentage of water consumption that can be attributed to the use phase, in comparison to other phases, is likely to remain similar in magnitude.

Table 53: Fuel Efficiencies for Different Vehicles (U.S. Environmental Protection Agency 2012)

| Vehicle | Miles / Gallons | Liters / Km | Water Consumption (Liters) |
|---|---|---|---|
| Honda CR-Z 2012 | 37 | 15.7 | 38,651 |
| Ford Fiesta FWD 2012 | 33 | 14.0 | 43,337 |
| Hyundai Sonata 2012 | 28 | 11.9 | 51,075 |
| Volkswagen Jetta 2012 | 34 | 14.5 | 42,062 |
| CAFÉ 2012 | 27.5 | 11.7 | 51,966 |

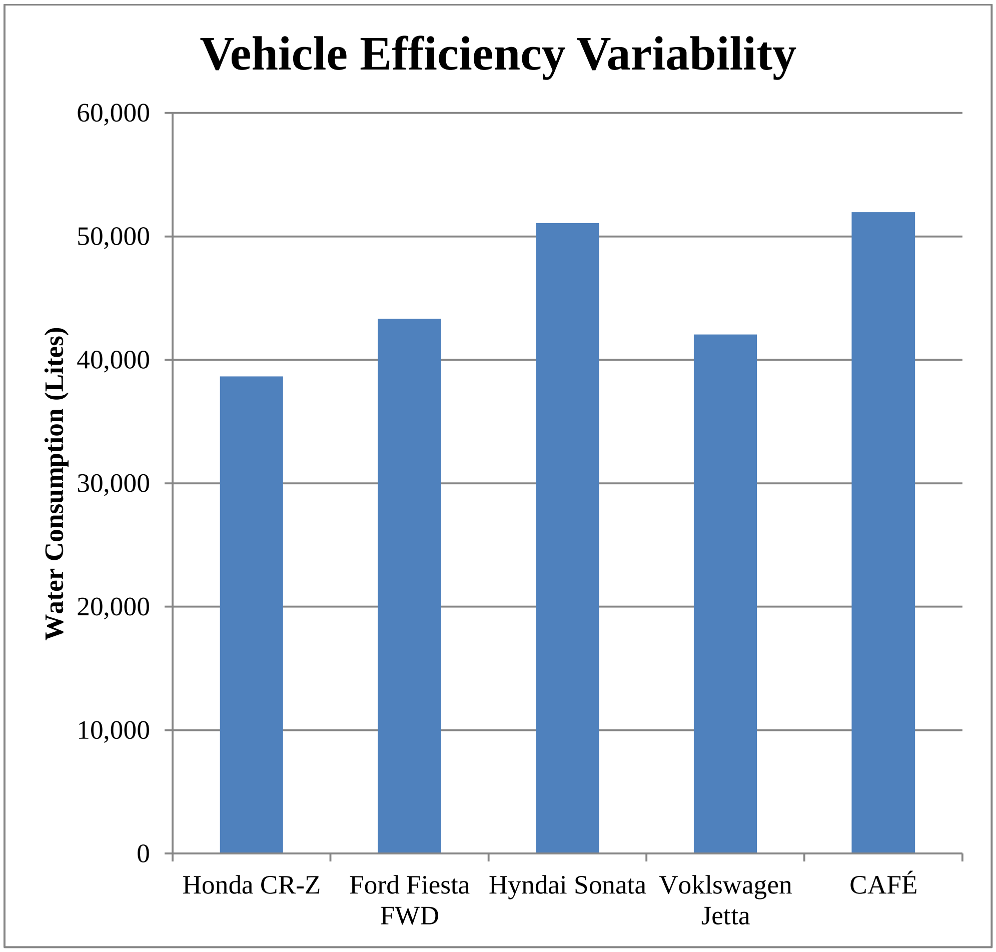


Figure 33: Fuel Efficiency Variability (U.S. Environmental Protection Agency 2012)

## 6.9 EcoInvent Data

After completing the analysis for water consumption, the data from EcoInvent was located on fuel production. The EcoInvent life-cycle inventory data for 1 kg unleaded petrol and diesel at a regional storage in Europe in which would imply a use of 857 of water per kilogram of gasoline as shown below in Table 54. Using a gasoline density of 0.77 kg/liter, this would imply a water use of 13,675 x 857 x 0.77 = 8,950,288 liters over the use phase of a gasoline powered car. If turbine use water is removed, the calculations arrive at about 14 per kilogram gasoline, which seems more realistic, but still 2 to 4 times higher than from (Gleick 1994). It is believed that the turbine water use may reflect indirect water use, potentially by the inclusion of water for the production of electric through hydroelectric dams or other from which would not be consistent with the scope of the analysis.

Table 54: Water Consumption/Use for 1 kg Gasoline

| **Production of 1 kg fuel** | **Petrol, unleaded, at regional storage (record #1573)** |
|---|---|
| Water Type | Amount [$m^3$] |
| Water, cooling, unspecified natural origin | 0.008531 |
| Water, lake | 8.12E-06 |
| Water, river | 0.001538 |
| Water, salt, ocean | 0.000461 |
| Water, salt, sole | 0.000895 |
| Water, turbine use, unspecified natural origin | 0.84278 |
| Water, unspecified natural origin | 0.00292 |
| Water, well, in ground | 0.00024 |
| Total | 0.8573 |
| Total minus “turbine use” water | 0.0146 |

### 6.10 Comparison of Water Consumption and Water Use

By reviewing the information from previous sections, a comparison can be made between the water consumption calculated and the EcoInvent data as shown in Table 55 and Figure 34. The EcoInvent data is assumed to be the water use because water only goes into the system without considering recycling. Although the water use is significantly higher than the water consumption, the difference is not as significant as that seen for the other phases. This could be because more water is lost is during extraction which simply cannot be replaced or recycled. The water may be injected into a well and lost.

Table 55: Water Analysis Comparison

| Water Consumption Data | EcoInvent Data |
|---|---|
| 51,965 | 153,735 |

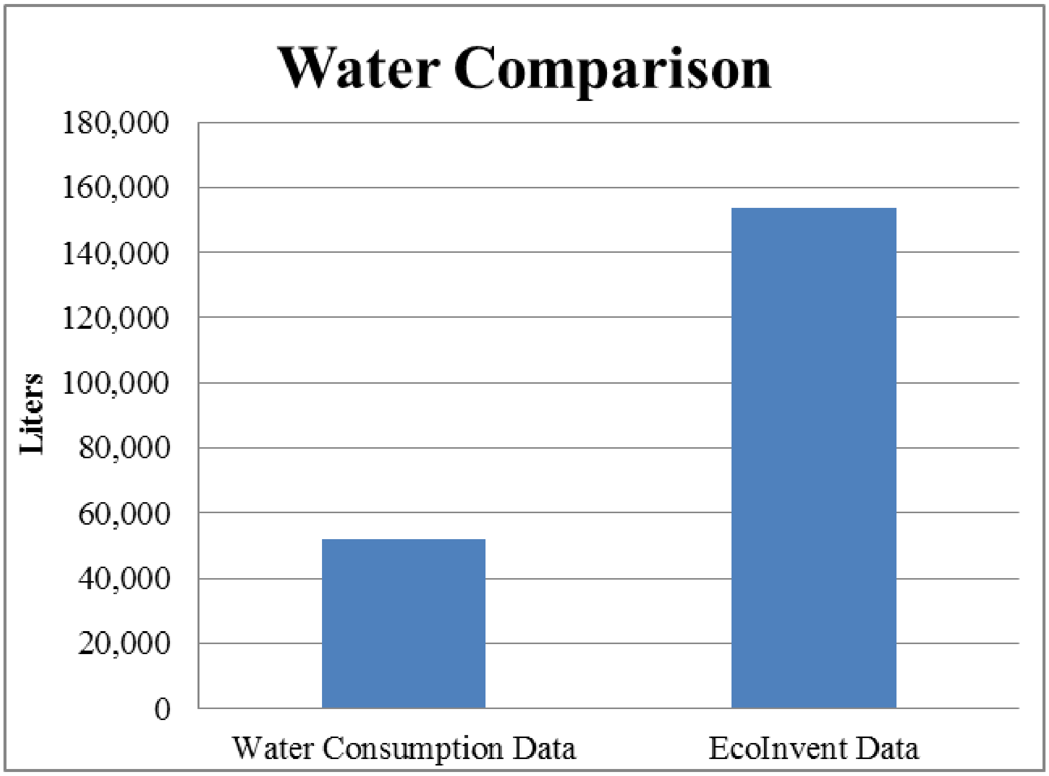


Figure 34: Water Consumption compared to Water Use (EcoInvent)

Either way, we would question using EcoInvent to calculate the water intake for fuel production. A more accurate way to measure the water input requirements would be to review the sustainability reports, of water meter data, for companies in the oil and gas industry.

## 6.11 Conclusion

As calculated in section 6.6 the total water consumption was 51,965 liters in the use phase assuming the minimum required efficiency according to CAFE standard, driving 100,000 miles (160,000 km) and the lowest water consumption for the production of fuels, 3.8 liters / liters

It was also shown that rather than fuel efficiency, the biggest impact in the use phase lies in the assumptions made to produce fossil fuels. In other words, the technologies and applications used for the production of fuels have the biggest impact in the water consumption for the use phase. Thus choosing fossil fuels that come from areas where water scarcity is not an issue would have the lowest impact, even if the absolute water consumption is the highest. Similarly, if the oil comes from producers using the latest and most efficient technologies, the water consumption absolute value would be lowest even if it does come from areas of water scarcity.

# CHAPTER 7:

# END OF LIFE

## 7.1 Scope

The model will only include water consumed for the dismantling, shredding, and processing of the materials of an automobile which can then be reused or disposed of separately from the rest of materials in the vehicle (Yen, Zullo et al. 2011). The scope is limited to the separation of materials that can then be reprocessed or disposed of properly, meaning that the water consumption in reprocessing the materials to their original form is not included because this would infringe upon the scope of production of materials and parts.

## 7.2 Data Sources

Published documents were used to identify the processes involved in disposing of a vehicle at the end of its useful life and values for material flows (Das, Curlee et al. 1995; Hendrix, Massey et al. 1996; Schweimer and Levin 2000; Castro, Remmerswaal et al. 2003; Funazaki, Taneda et al. 2003; Ferrão, Nazareth et al. 2006). However, these papers typically did not contain date on water use, and rarely provided a detailed description for each process, so other sources were used to calculate water consumption.

Companies involved in the design and manufacturing of recycling equipment like shredders and sink float separators, provided most of the water intake, and water consumption values for the different machines and processes (Metso 2010; A.W.C. Services LLC. 2011; Clean Washington Center 2011; Navarri 2011; Pinnacole Engineering 2011; Summit System 2011). Although much of the required information is provided publicly through the specifications for their equipment, individual engineers confirmed the water values for the different processes and assumptions.

Finally, EcoInvent V2.2 was also used to create an alternative model to use as a comparison. Although the data obtained from the reports in the data base did not contain descriptions of how the water was being used, of how much water was consumed, it provided a comparison of the existing trends. In the reports, water use was not clearly identified but it seemed to be how much water was measured going into a process without taking into account recycling (Hischier 2007; Classen, Althaus et al. 2009). In other words, the water values from these reports pertained to water use as opposed to water consumption.

In addition to selecting valid sources, an effort was made to ensure that the definition and scope mentioned in the work was consistent with the water consumption described earlier. Finding such sources proved challenging because many of the sources did not provide a definition for water consumption nor described the specific processes that led to the given value which is why contacting the engineers directly involved in the design process proved so beneficial. Although these individuals are not referenced in the thesis, their insights helped me to better understand how the machines they sold used and recycled water.

Despite efforts to ensure the use of quality data, uncertainties and limitations of data are inevitable and thus restrict a specific interpretation of results. However, comparisons of water consumption of the processing of the materials at the end of life, general trends in the water consumption, and differences between the data from EcoInvent and from other sources provide a directional trend and identify potential areas for water use reduction at the end of life.

### 7.3 Literature Review

Before starting the end of life water consumption analysis, literature reviews were completed to determine existing water models. Most authors, both in Europe and the U.S, were not concerned with the water consumption, but chose to focus on either on the environmental and economic implications of a car the end of life, or focused on the dismantling or shredding operations. The information available on water consumption at the end of life was limited at best. These various papers did provide a good overview of the various processes which take place.

A report by Volkswagen focused on the 10 year life-cycle inventory of four VW Golf A4 variants (ranging from 800-1,181 kg curb weight), as described in section 2.3, provides detailed assumptions and results on water use and consumption (Schweimer and Levin 2000). Although this study did include a description of the processes involve in at the end of life for a passenger vehicle, no specific descriptions were given about the use or consumption of water in the processes. A diagram of their processes can be found below, Figure 35, which give specific values for the flow of materials. What can be seen from the figure is that their end of life assessment included the removal of all fluids from as the first step, followed by the dismantling and shredding of components. This is similar to the processes that will be assumed and described in later sections although different assumptions will be made on how much material flows to and from each process. The authors also commented on a lack of references against which comparisons can be made (Schweimer and Levin 2000).

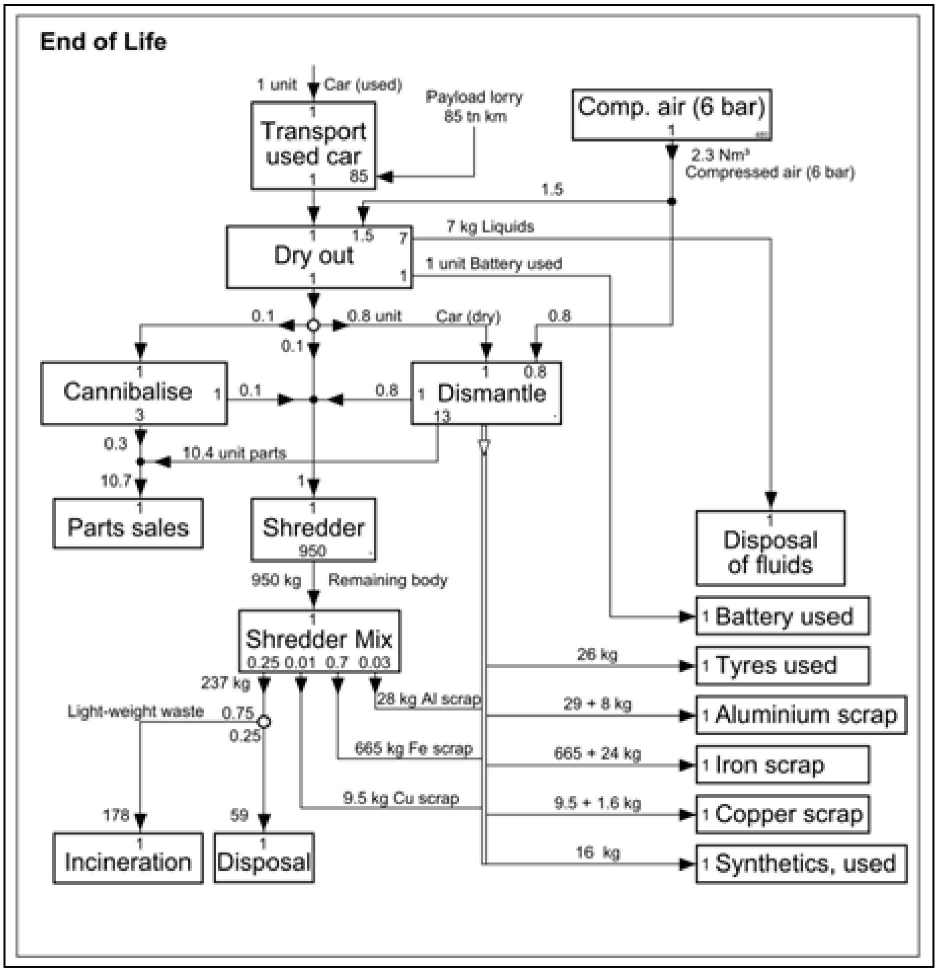


Figure 35: End of Life for A4 Golf case (Schweimer and Levin 2000)

An article examined on the Life Cycle Impact Assessment of the average passenger vehicle of the Netherlands focus on the existing dismantling and recycling practices in this country at the time of publications. (Castro, Remmerswaal et al. 2003). The average passenger vehicle was defined, having average weight and material composition.  A cradle to grave approach was taken with the return of the recycled materials to the material cycles in the end of life phase.  A particularity of this model is the detailed description of the Dutch collection and recycling infrastructure,  with current data for the dismantling, shredding, separation  and metallurgical  recycling processes (Castro, Remmerswaal et al. 2003). Although the paper contains a good review of the processes involved, including a mass balance that takes into account dismantling of reusable parts, it provides information aligned with European regulations as opposed to those existing in the U.S. It also does not provide information on how water was used, or consumed for the various processes. A diagram of their assumptions can be found below in Figure 36.

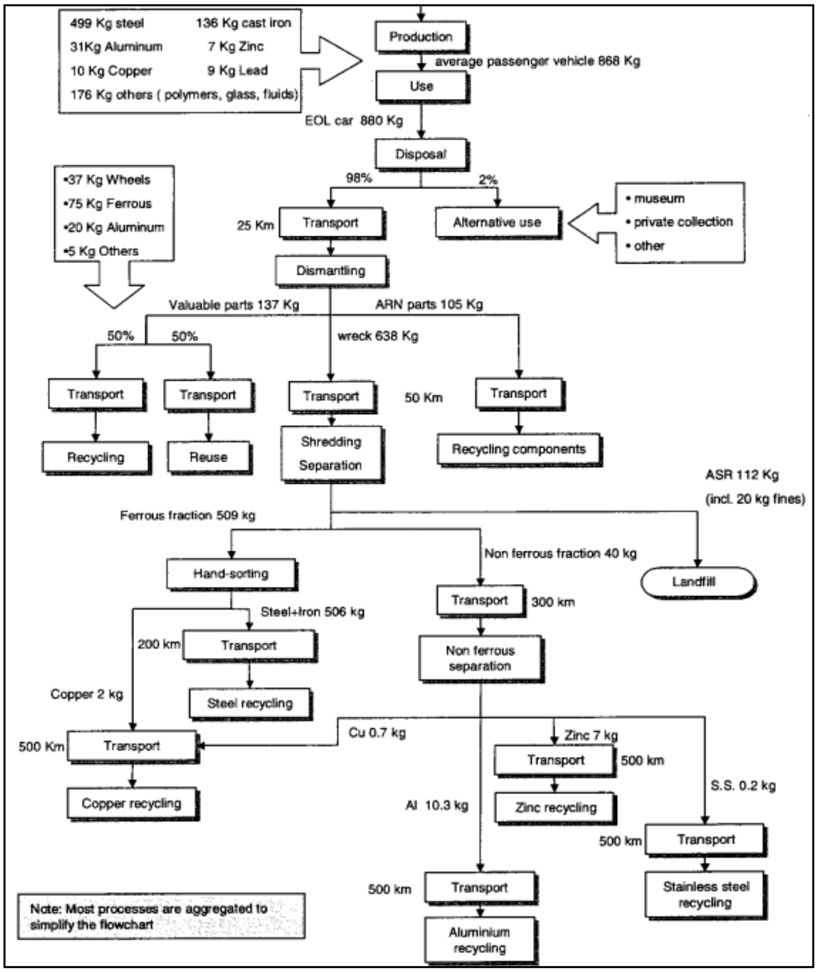


Figure 36: Recycling Life Cycle of Vehicle (Castro, Remmerswaal et al. 2003)

Other papers also described the processes in detail while providing actually numbers for material flows, including the water. One paper actually described the process the scrapping processes as consisting of dismantling a vehicle, shredding and sorting, recycling of each shredding reside, and landfill. The paper even included actual values for water inputs for the various systems. However, there was no description of what happened to the water after each process and how the water was measured. The data seemed to have come from a similar data base as EcoInvent, meaning that the water intake could be the total water usage without necessarily taking into account water recycling or water reuse (Funazaki, Taneda et al. 2003). An overview of their process can be found in Figure 37.

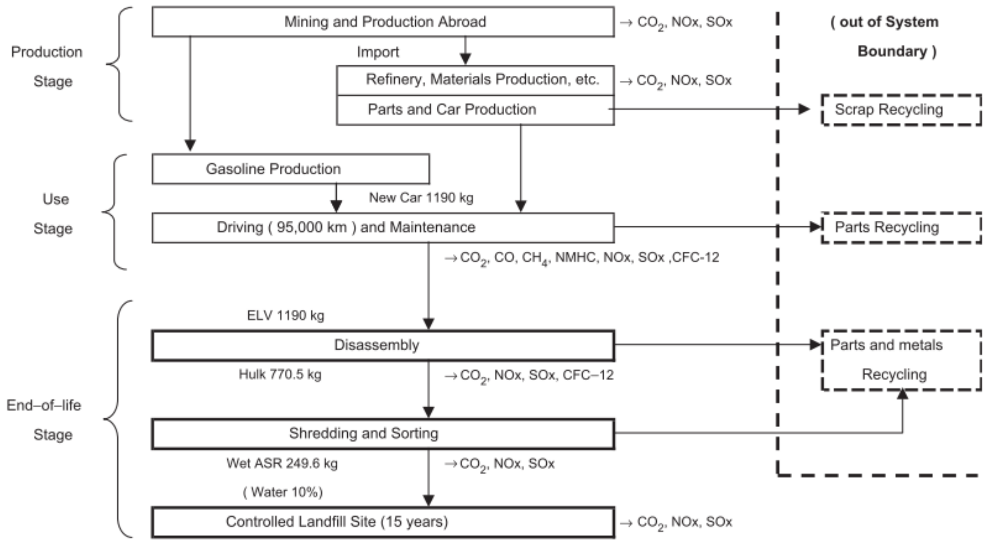


Fig. 1. System flows of the object vehicle and system boundary.

Figure 37: Scrapping Process (Funazaki, Taneda et al. 2003)

### 7.4 Material Composition

Because of the way materials are handled at the end of life for an automobile, a simpler material composition model can be used based on Table 2. All of the ferrous materials are treated as one, so combining all of them into one category is not only a good practice, but also a necessary requirement for the analysis. The same grouping assumption would go for all of the plastics and other non-metal materials because they are treated together at the end of life. Table 56 below shows the material composition model that will be utilized for this assessment which is basically a simplified version of the material composition presented earlier for an U.S gasoline powered vehicle.

Table 56: Simplified Material Composition Model (Das, Curlee et al. 1995)

| Material | Kg |
|---|---|
| Ferrous | 794 |
| Non-Ferrous Metals | 182 |
| Fluids | 80 |
| Plastics & Others | 325 |
| Total | 1,381 |

### 7.5 EcoInvent Data

The EcoInvent database contained an example of car disposal which included information on energy and water use in disposal processes for bulk materials. The data from report 145 had water numbers that added up to about 3039 liters per vehicle as shown in Table 57 (Spielmann, Bauer et al. 2007).

Table 57: Water Use in EcoInvent (Spielmann, Bauer et al. 2007)

| Water Value | Water Use (m^3) | Water Use (Liters) |
|---|---|---|
| Water, cooling, unspecified natural origin | 1.8509 | 1,851 |
| Water, lake | 0.0048 | 5 |
| Water, river | 0.3022 | 302 |
| Water, salt, ocean | 0.032 | 32 |
| Water, salt, sole | 0.0256 | 26 |
| Water, unspecified natural origin | 0.3455 | 346 |
| Water, well, in ground | 0.4779 | 478 |
| Total | -- | 3,039 |

## 7.6 Government Regulations

To understand the legal implications that exist with a car at the end of life, a literature review was done on government regulations for the states of Florida, New York, and Minnesota. The Environmental Compliance Manual for Automotive Recyclers of Florida requires that automobile recycles remove fluids including oils, refrigerants, and batteries (Florida 2006). Similarly, the state of Minnesota requires recyclers to remove the fuel, refrigerant, and batteries as soon as possible after vehicles enter the facility. Also, they require pressure cleaning in a closed-loop parts-washing machine that reuses wash water and filters waste fluids (Minnesota 2002). Finally the state of New York requires that recyclers drain fuels and refrigerants, and remove batteries (New York 2003).

What can be seen from the government regulations for these three different states is that all fluids and batteries must be removed prior to the scrapping process to comply with the law. Although the states have additional requirements in terms of how to properly handle other parts of the vehicle should they be in good condition and fit for immediate reuse, they typically do not require any additional steps prior to scrapping. It should be noted that there are differences between the government regulations in the U.S. and in the European Union. The European Union has more stringent regulations that require the individual removal of many more components prior to starting the scrapping process.

## 7.7 Scrapping Process

### 7.6.1 Overview

Based on the literature review of published papers and government documents, the initial recycling efforts can be expected to consist of manual and mechanical separation. Reusable components and materials with high value are sometimes manually removed from the car by dismantlers. These materials are removed by hand because separate piles of aluminum and steel are worth significantly more than a commingled pile of the two metals (Hendrix, Massey et al. 1996). For this analysis, it will be assumed that the only items removed during the dismantling of a vehicle will be the fluids (Oil, coolants, fuel, etc.), the batteries, and the tires. The tires are usually removed from the vehicle prior to scrapping, if not required by government regulation, by common practice amongst recyclers (Hendrix, Massey et al. 1996).

Following the dismantling , the vehicle is sent to a shredder, shredded, and the pieces mechanically separated based on the properties. The car will be sent into a hammer mill or similar piece of equipment which reduces the vehicle to fist-sized pieces. The ferrous metals are magnetically separated into one pile, and the non-ferrous metals are generally separated using an eddy-current machine into another pile. The ferrous metals are then sold to a smelter. The non-ferrous metals, which are worth significantly more, are then separated into specific types of metal, either by the shredder or another company. The remainder of the car, is generally called Automotive Shredder Residue or "fluff". This shredder residue, which consists of plastics, rubber, glass, dirt, fluids, and other materials, is either sent to a landfill, or separated and partially recycled (Hendrix, Massey et al. 1996). An overview of the basic process can be found in Figure 38. Water is use in the shredder and to separate the automotive shredder residue.

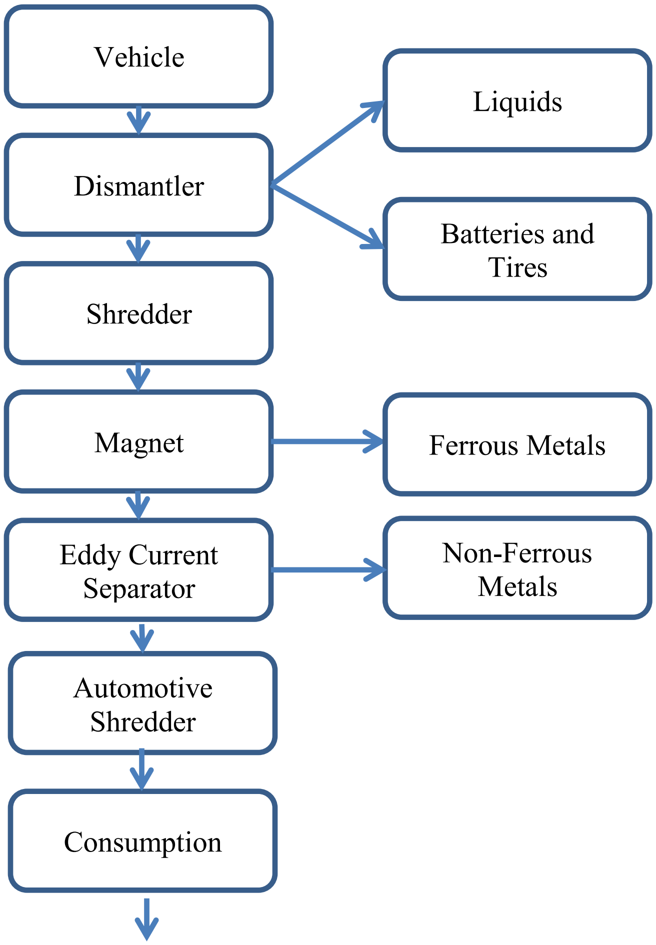


Figure 38: Vehicle Dismantling and Separation Process (Hendrix, Massey et al. 1996)

### 7.6.2 Dismantler

As mentioned before, the dismantling process removes all the fluids, batteries, and tires from the vehicles. This process is typically referred to as depollution (Ferrão, Nazareth et al. 2006). Although other components can be removed and recycled depending on condition of the vehicle, year, made, etc., for this analysis, it will be assumed that except for the fluids, batteries and tires, the rest of the vehicles remain together as it is headed to the shredder. This assumption would be the worst case scenario for the end of life of a vehicle and would ensure that the situation in which case there is no other form of recycling is taken into account. Having said this, one can see how the water consumption values would only be lower if more of the vehicle could be recycled as is prior to the shredding.

For the process of dismantling, it is assumed that the fluids, batteries and tires were removed either manually or with the help of some mechanical equipment. Either way, there would be no direct water consumption values that would be consistent with the definition set forth for water consumption in this paper. Although one could consider the water consumption, for instance, of the facilities, the transportation, or machinery, it would not fit within the scope and would be nearly impossible to measure as the values would significantly vary on a case to case basis.

The removal of the fluids would account for 80.29 kg of the total weight of the vehicle (Das, Curlee et al. 1995). The tires will be assumed to be made completely of rubber and account for 95.8 kg of the total material of the vehicle. Although this is a simplification of the material composition for the tires, it facilitates calculation and has an insignificant effect on final water consumption value for the end of life. The removal of the battery would account for 10.2 kg as an average for different types of batteries for different types of vehicles (Ferrão, Nazareth et al. 2006). The battery will be represented as a plastic. For this analysis, this simplification makes an insignificant effect on the final value and facilitates calculations. By the removing the fluids and batteries, the original weight composition of the vehicle would drop to 1,194.4 kilograms into the next step of the disposal process.

### 7.6.3 Shredder

#### 7.6.3.1 Overview

Following the dismantling or depollution, the next step of the scrapping process is shredding. Shredding can vary depending on the machinery and the steps selected, but the process is relatively similar regardless of the variables. First, a car would be placed in a press and compressed to reduce its effective volume. This allows for easier transportation, storage, and handling of the vehicles. The vast majority of end of life vehicles are purchased as flat bodies from dismantlers (A.W.C. Services LLC. 2011). Some are also purchased directly from consumers. Dismantlers are required to depollution vehicles prior to delivery, as explained in an earlier section. A failure to comply might cause a rejection of the vehicle or the entire batch. The process starts by loading scrap onto the belt that conveys it to the shredder. Although there are three different kinds of shredders in operation in industry, the paper will focus on the wet shredders as they would consumed the most water. It should be noted that using other types of shredders can help reduce the water use or even water consumption which would be important for regions where water is a scarce resource. In wet shredders, water is added prior to shredding to limit the impact of explosions and to keep the dust to minimal levels. Damp shredders add less water; dry shredders do not add any water (A.W.C. Services LLC. 2011).

#### 7.6.3.2 Company Data

The feed rate for the shredder is controlled by the feed roller, which pushes the scrap against a rotor equipped with a number of hammers. These hammers shred the vehicle into small pieces. The throughput of a shredder is mainly determined by the design of the shredding chamber, rotor design and by the motor that drives the system. (A.W.C. Services LLC. 2011). Material throughput capacities range from 30-350 tons/hr. or 500 – 5800 kg/min (Metso 2010).

A significant feature in the shredders is the Water Injection System which controls shredder smoke, dust, and visible pollution. It also produces steam which displaces oxygen in the mill, reducing the risk of explosion (Metso 2010). Although some systems were found in the literature search and from the manufacturers of shredders for waste water recycling, they were not commonly used, so it can be assumed that the water either evaporates due to the heat created during shredding, or it is absorbed by some of the materials in the vehicles. This was also confirmed by design engineers at the various shredding companies that were contacted.

The water consumption values were calculated using two methods. First, one company actually gave the water injection values for their system. Texas Shredders, as part of Metso Corporation, BEST's Smart Water Injection System works to control dust, smoke and fire in the shredder. It injects a known volume of water-an average of approximately five gallons per ton into the rotor chamber (0.019 liters per kg of shredded material). The system is programmed to dispense the minimum amount of water required to provide proper distribution and good evaporation (Metso 2010). Since they water into the shredder is either evaporated or absorbed into the product, this value can be assumed to be the water consumed. Secondly, the water into the system was calculated using the maximum flow a water injection system from another company coupled the maximum input capacity for the shredders. Pinnacle Engineering water injection system Model P-3C-5-300-1 has a maximum flow rate of 20 gallons per minute (75.71 liters per minute) (Pinnacole Engineering 2011). As mentioned before the input capacity of shredders, as per the specifications provided by Texas Shredders, is up to 5.833 tons / min (5800 kg/min) which couple with the maximum capacity of the water injection system would give a value of 3.48 gallons per ton (0.013 liters per kg of shredded material). Although there is a difference between these two values per ton, what should be considered is the small amount of water that is actually consumed in shredding the material in the per kilogram basis. The higher value will be used as it provides the worst case scenario. Using the water consumption per kilogram of 0.019 with the material input into the shredder from section 7.6.2 of 1,194.4 kilograms, the total water consumption for the shredding of the car is 14.34 liters.

### 7.6.3.3 EcoInvent Data

In addition to finding information from various manufacturers on the water intakes and water consumption for the end of life shredding operation, information was also found from the EcoInvent database, as seen in Figure 39**.** What is surprising is how much the water use differs in the EcoInvent database to that in gathered from the manufacturers of shredding machines. This could be because of a difference in the scope. The EcoInvent database may include a wider set of operations. A more detailed description of the scope could not be located, specially relating to the water intake and tracking in the system. The water consumption gathered from publicly available machinery information was also the water use since all of the water that went into the systems was evaporated or incorporated into the products which make the difference in the two values more surprising. The description of the various processes involved in the water numbers in EcoInvent could more extensive by including direct fuel consumption and cleaning the systems which could explain the difference in values. There section under "Turbine Use" which refers to the water use in the production of the energy used for the system was not included because it would be outside of the scope and relate to the production of energy. The total water use based on the EcoInvent database was 1,781 liters as shown in Table 58.

Table 58: Water Use for Shredding Based on EcoInvent (Spielmann, Bauer et al. 2007)

| Material | Liters / Kg | Report Number | Kg | Percentage | Liters | Percentage |
|---|---|---|---|---|---|---|
| Steel | 1.588 | 2122 | 793.8 | 63.99% | 1260.6 | 70.80% |
| Aluminum | 2.169 | 2089 | 154.2 | 12.43% | 334.6 | 18.79% |
| Copper | 2.043 | 2095 | 20.4 | 1.65% | 41.7 | 2.34% |
| Zinc | 6.414 | 2131 | 7.3 | 0.59% | 46.6 | 2.62% |
| Shredder Residue | 0.367 | 2230 | 264.9 | 21.35% | 97.2 | 5.46% |

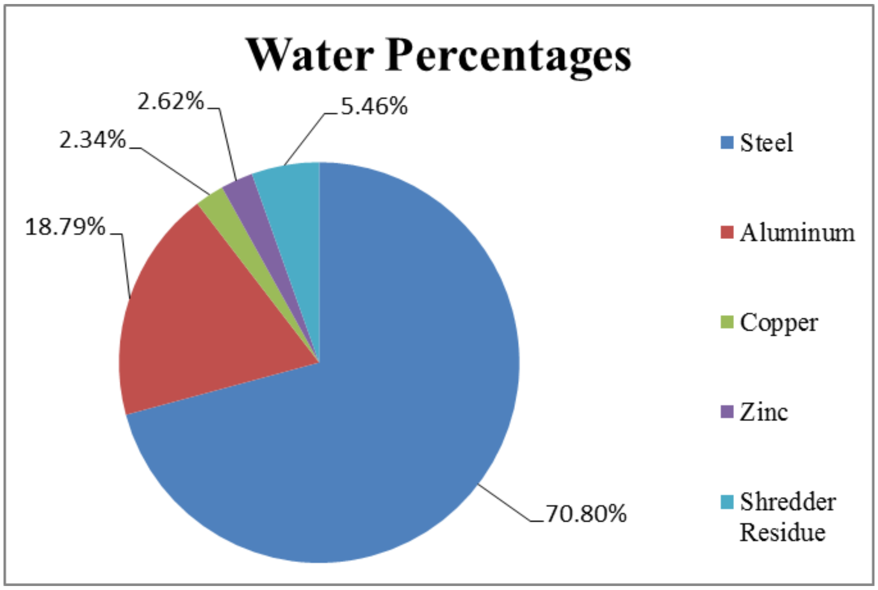


Figure 39: Water Consumption Percentages based on EcoInvent (Spielmann, Bauer et al. 2007)

### 7.6.4 Magnetic Separation

After the scrap is shredded into fist-size pieces, it is separated by a magnet into a ferrous and a non-ferrous waste stream. It is important to understand that this separation is not perfect as some ferrous pieces are still connected to non-ferrous pieces, causing a certain degree of impurity in each stream. One example is copper wire from electric motors that remains attached to ferrous components in the ferrous stream. The resulting ferrous scrap is the finished product of the ferrous stream. Depending on its purity, it is sold accordingly (A.W.C. Services LLC. 2011). Taking into account the water consumption definition set forth at the beginning of the paper, one would see that no water is actually consumed in this process. The amount of ferrous material collected at this point with the magnet is expected to be in up to 99 % which results in a material flow out of the system of 40935 kilograms (Ferrão, Nazareth et al. 2006). No water is directly consumed in this process as the materials are separated without the need of water for processing or cleaning.

### 7.6.5 Eddy Current Separator

The non-ferrous scrap is often screened to fractions of similar size, which are processed separately. An Eddy Current System, which uses principles of electromagnetic induction in conducting materials is used to isolate non-ferrous metals from this stream (A.W.C. Services LLC. 2011).

Eddy current separation is an effective way of removing non-ferrous metals from stream of industrial or municipal waste. The process is used to separate aluminum and copper from car scrap and to remove metals from recycle glass (Rem, Leest et al. 1997). This non-ferrous metal fraction contains mainly zinc, brass, copper and aluminum. Some shredding companies ship this product to companies specializing in the further separation of these metals. The aluminum is typically sold to a smelter, whereas the zinc, brass and copper are sold to companies that further separate this material (A.W.C. Services LLC. 2011). This process can remove up to 95% percent of the non-ferrous metals from the residue which results in a weight out of the system of 236.25 kilograms (Ferrão, Nazareth et al. 2006).

The second output of the eddy current station contains almost all of the non-metal items. The remaining items mainly consist of plastics, glass, fabric, foam and a small fraction of metals, referred to as shredder residue or fluff. This is typically of lesser value. It is sometimes sent to be separated and recycled in but whatever is left has to be disposed of in landfills. This shredder residue has to be monitored for levels of contaminations. Shredder residue may actually still have positive value, especially in those states that allow the use of fluff as alternate daily cover in landfills (A.W.C. Services LLC. 2011). Just like magnetic separation, water is not directly used or consumed in the eddy current separator.

### 7.6.6 Shredding Residue Separation

#### 7.6.6.1 Introduction

Meeting market quality requirements for recycled materials from shredder residue is difficult and expensive. Shredder residue is comprised of over 20 different plastics, several types of rubber and 12 different metals from automobiles alone (Sullivan, 1998). Considering processing costs, recyclable material recovery may only be a viable option for certain high value components from shredder reside. The processing required to recover marketable materials could involve many mechanical separation and purification steps. Significant energy and material inputs, such as water for washing, natural gas for heating, and electricity are required (Boughton and Horvath 2006). Although there are various existing methods for the extraction of plastics, for this thesis, it will be assumed that the residue goes through a sink float separator because it was the method most commonly referenced in published material and in recyclers as the system of choice.

#### 7.6.6.2 Overview of Sink Float System

The float-sink containers have the task of separating plastics with different densities from each other in a fluid, in a closed loop system (Summit System 2011). The separation container consists essentially of a tank that is filled with liquid and a screw for material transport after separation. Depending on the separation task, the plastic to be separated is dosed into the separation container with a stirrer or applied under the surface by screws (Summit System 2011).

The float/sink concept relies on the specific gravities of the various materials processed in the tank relative to the specific gravity of the base solution in the tank. Those materials with a specific gravity higher than that of the base solution will sink while those with a lower specific gravity will float. The specific gravity of the base solution can be changed as necessary though the addition of the various chemical additives (Polymer Recovery Systems 2011). The material is deposited on to the surface of the water in the tank. Heavy material sinks to the sloped bottom of the tank. A drag conveyor, which continually sweeps the bottom surface, conveys this material to an above-water discharge. Buoyant material is conveyed to the opposite end of the tank where it is discharged by a partially submerged screw conveyor or a rotating paddle (Polymer Recovery Systems 2011).

The separated float and sink components are discharged at a common end location so either component can be easily routed to a washer/dryer or other post process plastics machinery (Polymer Recovery Systems 2011). An overview of the system can be found below in Figure 40.

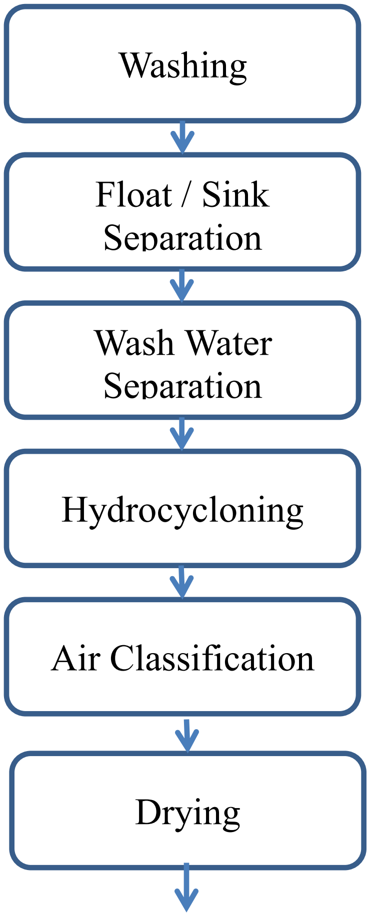


Figure 40: Sink Float System Overview

#### 7.6.6.3 Sink Float System

A float-sink separation operation is rarely alone but rather consists of system of machines connected together to recycle the plastics. Cleaning systems generally consist of a combination of washing, float/sink separation, and/or hydrocycloning stages (Summit System 2011).

The washing stage is designed to remove remaining labels, adhesive, or product residues on the HDPE flakes. Some reclaimers use water-based systems, while others use water and chemical based systems employing detergents, emulsifiers or anti-foaming agents to clean the regrind and liberate the remaining labels for subsequent removal (Clean Washington Center 2011).

Float/sink separation uses water to separate materials based on their density or specific gravity. Material with a specific gravity greater than water will sink as explained earlier. Materials with a specific gravity less than water will float. HDPE has a specific gravity less than water and will float. (Clean Washington Center 2011).

Float/sink separation tanks are usually equipped with a series of paddle wheels that agitate and help loosen contaminants from the HDPE flakes. A paddle wheel is frequently used to remove the floating HDPE flake to a dewatering or spin-drying station to remove dirty wash water. Float sink separation can occur before or after washing, or both, depending on the specific system (Clean Washington Center 2011).

After washing, the HDPE flakes are separated from the dirty wash water by filtering, or spin-drying. The dewatered flake is usually then rinsed and dewatered again, to remove adhesives or contaminants that may have resettled on the flakes (Clean Washington Center 2011).

The dirty wash water is normally filtered and blended with fresh makeup water for reuse in the wash process. Process wash water that is dumped to the sewer is treated to comply with all local regulations for water emissions (Clean Washington Center 2011).

A hydrocyclone is a vertical cylindrical vessel that uses gravity, centrifugal force and differences in material density to classify solid particles contained in a liquid stream. Hydrocyclones may be used on their own or in conjunction with sink/float systems to separate HDPE from other plastics and contaminants. They may also be used to remove contaminants from the wash water (Clean Washington Center 2011).

Air classification "elutriation" can occur at any of several points during the recycling process and may occur more than once. Air classification systems remove fiber, fines, powder, paper, film, and foam from HDPE regrind, which reduces overall contamination levels in subsequent processing stages making them more efficient. Air classification removes any lighter film and fiber portions present in HDPE flake that are not easily separated in subsequent washing and cleaning stages (Clean Washington Center 2011).

During drying the dewatered flakes are passed through a dryer that utilized heated air to remove all residual surface moisture from the clean flakes. The clean flakes may be sold for use in this form or melt processed (Clean Washington Center 2011).

The plant is designed to sediment the suspended dirt particles in 3 consecutive steps. The water back flowing from the Sink-Float Tank is discharged into a vessel and from there to an intermediate storage sink. The water discharged from the centrifuges flows directly to this sink. Once filtered, the cleaned water is stored in large pools for recirculation. These pools also serve as storage for the large water quantity in closed circuit (Navarri 2011).

The steam cleaning system is an important sub-system for environmental control and working place hygiene. The aspiration hood with fan installed on top of the processing chamber collects the steam produced during the process and ducts it to the condensing column, which is normally installed outside the building. Stainless steel sprinkler system condenses the steam and dust. The water is released at the bottom and ducted to a vibrating sieve (Navarri 2011).

## 7.8 Water Use and Water Consumption

### 7.7.1 Water Use

The water within a float sink separator flows in a closed loop and is treated in a water treatment plant, meaning that the water is recirculated thus the discharge of wastewater and the water consumption are minimal. This is both environmental friendly and ultimately costs the recyclers less money by consuming fewer resources. The water use for the sink float system can be found below in Table 59.

Table 59: Water Use for Sink Float Tank (Navarri 2011)

| Measurements | Value |
|---|---|
| Water in closed loop | 200 Liters / Minute |
| Production Averages | 1.5 - 2.0 (25 – 33.33) Tons / Hour (Kg / min) |

For a typical post-consumer plastics washing and recycling plant with a capacity of about 2 tons / hour (33.33 kg / min) the water use in a closed loop is as follows in Table 60.

Table 60: Water Use in Closed Loop (Navarri 2011)

| Washing water | Flow Rate (Liters / min) | Flow Rate (Liters / Kg) |
|---|---|---|
| Sink-Float Tank | 200 | 6 |
| Turbowash | 150 | 4.5 |
| Dynamic Centrifuge | 25 | 0.75 |
| ML 1400 | up to 250 | Up to 7.50 |
| **Cooling water** | **Flow Rate (Liters / min)** | **Flow Rate (Liters / Kg)** |
| Turbowash | 13 | 0.39 |
| Dynamic Centrifuge | 13 | 0.39 |
| Densifier | 60 | 1.8 |
| Steam Cleaning | 70 | 2.1 |
| ML 1400 | 70 | 2.1 |

Using the system described above, a closed loop system would use about 610 lit/min, which coupled with a 33.33 kg per minute capacity, assuming the highest possible plastic yield, would yield a water use value of 18.30 liters per kilogram of water or 4,323 liters for handling the shredder residue.

### 7.7.2 Water Consumption

As mentioned in the previous section, the values listed for the separation system were for those of water use. The majority of the water is reused back into the system in the form of a closed loop system. The actually water consumption values due to evaporation, including a steam cleaning system are estimated to be about 1.5-2 m3/h or about one liter per kg of material as shown in Table 59 (Navarri 2011). This value can be higher if the production of the processed material is not as high or if the efficiency were to drop of how the water was disperse. The water that is not immediately reused must be treated. Post-consumer plastics contamination for 1.3 t plastics/h corresponds to about 130 kg/h which results in a water treatment of about 0.1 liters per kilogram of plastic processed or basically a tenth of water must be treated for every kilogram of plastic processed. The water treatment values will differ depending on the efficiency of the process.(Navarri 2011). The water consumption values for the entire system can be found in then 1 liter per kilogram of material in the sink float separation system.

Coupling the material input into this process of 236.25 with the water consumption of 1 liter per kilogram, the calculated water consumption for this step at the end of life for a vehicle is 236.25 liters. This is significantly higher than any other part of the process and encompasses most of the water consumption for the end of life of a vehicle within the scope set forth at the beginning of the paper.

## 7.9 Summary of Water Consumption

The water consumed at the end of life for a vehicle is 259 liters as shown in Table 61. Most of the water is consumed in the sink float separator system is the result of the water that is evaporated to separate the materials and the water use in the steam cleaning processes. Although the shredding residue only encompasses a small part of the vehicle by weight, they have most of the water consumption as part of the end of life of a vehicle. As can be seen, the water consumption values for the end of life for the vehicle are significantly lower than those presented in the EcoInvent database. This may be a result of a difference in scope. The EcoInvent database scope may have included processes and water intakes into a system which are not accounted for in this paper because of the difference in scope. The water consumption in this paper focused on the processes involve directly in the disposal of the vehicle. The EcoInvent may include water us for the facilities or include additional processes to process the bulk materials into reusable material. No detailed descriptions are given on the report so it is unclear as to what consisted of their scope. Additionally, the EcoInvent database only seems to take into account water intake without necessarily measuring how much water is released or consumed in the processes. Our research also showed that EcoInvent significantly over estimated the water intake for the shredding operations which would lead me to question the validity of their data for this phase of a vehicle. A more appropriate approach would be to review water recommendations directly from equipment handbooks as we did.

Table 61: Water Consumption per Process

| **Process** | **Water Consumption (Liters / Kg)** | **Material into System System(Kg)** | **Water Consumption (Liters)** | **Ratios** | **Sources** |
|---|---|---|---|---|---|
| Dismantling | 0 | 1381 | 0 | 0 | (Metso 2010; Metso 2010) |
| Shredding | 0.02 | 1195 | 23 | 9% | (Ferrão, Nazareth et al. 2006) |
| Magnetic Separation | 0 | 1195 | 0 | 0 % | (Ferrão, Nazareth et al. 2006) |
| Eddy Current Separator | 0 | 410 | 0 | 0 % | (Ferrão, Nazareth et al. 2006) |
| Sink Float Separator System | 1 | 236 | 236 | 91% | (Navarri 2011) |
| Total Water Consumption | 0.22 | -- | 259 | 100 % | |

## 7.10 Conclusion

This chapter focused on an assessment of the amount of water consumed at the end of life for a mid-sized gasoline powered US vehicle. According to my analysis, 259 liters of water is consumed for the dismantling, shredding, and processing of a US vehicle at the end of life. Even though the processing of the plastics can require significant amounts of water, with the use of waste water treatment technology, much of it can be recycled and reused.

Using water use found in the EcoInvent V2.2 database resulted in 3,039 liters of water for the disposal. The EcoInvent supporting information did not provide any background information regarding what assumptions or definitions were given for the water numbers. The description merely said that the values represented information for the bulk materials and explained that there could have been uncertainty in methodology. There is also no description of what happens to that water after it goes into the system. Using publicly available machinery information, it was found that the water use would be 4346 liters, most of which is part of the shredding residue separation process, which is in the same scope as that of the EcoInvent database. The biggest discrepancies between the

EcoInvent data and publicly available information were found in the water intake to the shredding operation. The EcoInvent database had 1,781 liters for water intake, while the machinery data suggested a value of 23 liters.

# CHAPTER 8:

# INDIRECT WATER CONSUMPTION

## 8.1 Scope

After going through each of the stages for the life of a vehicle to quantify the total direct water consumption, the scope of the analysis was broaden to examine indirect water consumption. The work of this thesis investigated the water requirements for the energy consumed in the production of materials, parts production, and final assembly. It seemed like an interesting concept as part of the analysis to better understand the correlation between energy consumption and water consumption and its magnitude when compared to stages for the life of a vehicle. As it will be shown, this value can actually have a large impact in the overall water consumption. The calculations of this chapter disregarded the energy consumption for the end of life because it is minimal when compared to the energy consumption for the other phases (Sullivan and Cobas-Flores 2001).

## 8.2 Literature Review

The study completed by Volkswagen focusing on the 10 year life-cycle inventory of four VW Golf A4 variants pointed to production of energy for the life of a vehicle as an important consumer of water as originally mentioned in section 2.3 (Schweimer and Levin 2000). The authors report that “water consumption of 95 $m^3$ (95,000 liters) per car can be broken down into that needed for electric power generation (46 $m^3$), fuel production (23 $m^3$), car washing (8 m3), material production (10 $m^3$) and other factors (9 $m^3$)” (Schweimer and Levin 2000). The authors point to the production of electric power as being a major aspect to be considered, especially given the link between energy and water. Although no other sources developed this correlation as part of the life cycle of a vehicle, this report had enough validity to make a more in depth analysis worth the time in hopes of identifying additional important trends.

Other papers established how important water is for the production of energy (Gleick 1994; Feeley Iii, Skone et al. 2008; Fthenakis and Kim 2010). Supplying energy requires water in all aspects of generation and distribution. Many of the fuels required for producing energy require large quantities of water for extraction or mining and are potentially from regions with limited water resources (Yen 2011). Similarly, large amounts of water are required for processing, refining, or distributing these fuels, whether it is in terms of water for refining petroleum or water used to transport coal slurry through vast pipelines. Even more water is required for burning these fuels through thermoelectric power generation as these power plants consume and withdraw significant amounts of water for cooling, maintenance, or other functions essential for their operation (Yen 2011).

## 8.3 Methodology

To create the energy consumption model, two different approaches were used. First, data was gathered from previous studies completed for the entire life cycle of the vehicle. These studies had recorded the energy consumption for the different phases; this information was then coupled with the water consumption for different energy sources to calculate an initial assessment of water consumption (Sullivan and Cobas-Flores 2001). In the second approach, a more detailed a set of data points were used, which separated the total energy consumption by source for the manufacturing and assembly stages (Sullivan, Burnham et al. 2010). The energy consumption from this data was also coupled with water consumption for the various energy sources to calculate the water consumption.

Water consumption for the production of energy was also readily available. A thesis recently written was used to calculate water consumption in energy production for several reasons (Yen 2011). First, the data presented was consistent with my definitions of water use and water consumption. Secondly, the thesis summarized existing work on the subject by providing high values, low vales, and comparing several sources. And lastly, this thesis was recently submitted so it has of the latest trends and data points on the subject (Yen 2011). The water consumption for the production of energy is broken down into two sections: the extraction and production of fuels, and electricity production as shown below in Figure 41. Although transportation of the energy still plays a role, it does not consume water directly.

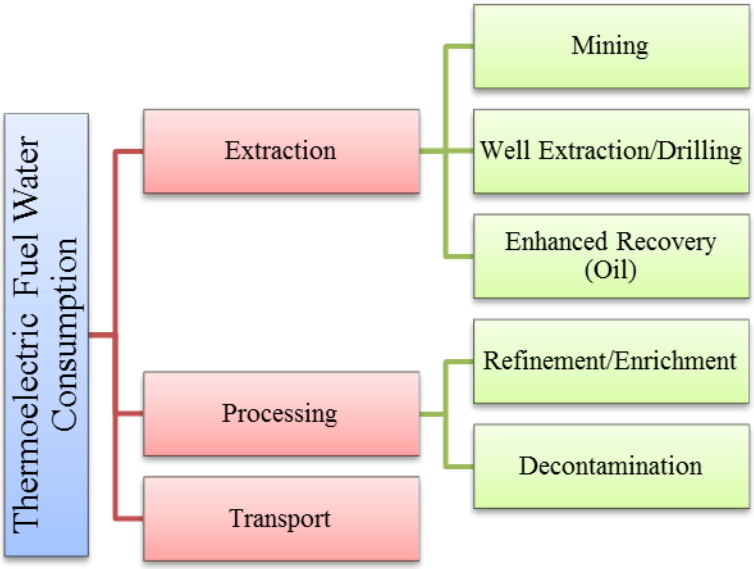


Figure 41: Overview of Water Consumption in Thermoelectric Fuels (Yen 2011)

### 8.4 Water Consumption for Extraction and Production of Fuels

Water consumption for the production of fuels can generally be divided into water consumed in extracting or mining raw materials, in refining these materials into usable fuels, and in distributing or transporting these fuels. Water consumption for oil and natural gas can be attributed to onshore or offshore exploration and extraction, refining, fuel transport, as well as water required to decontaminate any water extracted from crude oil. While natural gas extraction requires only water for drill coolant, many producers have looked to heavily water-intensive secondary and tertiary recovery methods ranging from water flooding to forward combustion processes in order to increase the amount of recovered crude oil. Coal production is water intensive in terms of water for surface or underground mining, washing and decontamination, and transport as slurry or by freight train. Similarly, for nuclear fuel, water consumption can be attributed to dust suppression and mining, ore decontamination, and uranium milling and enrichment (Yen 2011). A summary of the water consumption data for the various fuels can be found below in Table 62.

Table 62: Production Fuel Type Water Consumption (Gleick 1994; Fthenakis and Kim 2010; Yen 2011)

| Material | Process | Sub-Process | Water Consumed (l/kWh) | Total (l/kWh) |
|---|---|---|---|---|
| **Coal** | Mining | Surface | 0.011 | 0.473 |
| | Processing | Benefication | 0.042 | |
| | Transport | Slurry Pipe | 0.42 | |
| **Natural Gas** | Processing | Purification | 0.057 | 0.087 |
| | Transport | Pipeline | 0.03 | |
| **Nuclear Fuel** | Mining | Underground | 0.004 | 0.185 |
| | Processing | Milling | 0.083 | |
| | | Conversion | 0.042 | |
| | | Enrichment | 0.045 | |
| | | Fabrication | 0.011 | |

## 8.5 Water Consumption for Electricity Production

In addition to water consumption required for fuel extraction and processing, water is consumed in the production of electricity, in the form of evaporative losses and facility requirements in thermoelectric power plants. Although the actual water consumption values differ, the required water to produce energy based on the different fuels is similar in nature and thus has similar magnitudes. Thermoelectric plants consume water to produce electricity through their turbines as the fuels heat up the water for steam generation (Yen 2011). The one exception is hydroelectric power which mainly uses water from reservoirs passed through to drive turbines, although there is a significant amount of evaporative and seepage losses from required water reservoirs depending on the surrounding environment and climate. Renewable energy consumes water during the fabrication and maintenance of the facilities (Yen 2011). A summary of the water consumption for the different configurations of the various fuel sources can be found below in Table 63.

Table 63: Water Consumption in Electricity Production (Yen 2011)

| **Energy Type** | **Cooling Configuration** | **Boiler Type** | **Water Consumed (l/kWh)** | **Sources** |
|---|---|---|---|---|
| **Coal** | Once-Through | Subcritical | 0.522 | (Gleick 1994; Feeley Iii, Skone et al. 2008; Fthenakis and Kim 2010) |
| | | Supercritical | 0.428 | |
| | Cooling Tower | Subcritical | 0.269 | |
| | | Supercritical | 0.469 | |
| | Cooling Pond | Subcritical | 0.39 | |
| | | Supercritical | 0.242 | |
| **Energy Type** | **Cooling Configuration** | | **Water Consumed (l/kWh)** | |
| **Oil or NG** | Once-Through | | 0.341 | (Gleick 1994; Feeley Iii, Skone et al. 2008; Fthenakis and Kim 2010) |
| | Cooling Tower | | 0.606 | |
| | Cooling Pond | | 0.42 | |
| **Nuclear** | Once-Through | | 0.519 | (Gleick 1994; Feeley Iii, Skone et al. 2008; Fthenakis and Kim 2010) |
| | Cooling Tower | | 2.362 | |
| | Cooling Pond | | 1.7 | |
| **Energy Type** | **Location** | | **Water Consumed (l/kWh)** | |
| **Hydro** | United States Average | | 17 | (Gleick 1994) |
| **PV Solar** | United States Average | | 0.023 | (Gleick 1994; Harto, Meyers et al. 2010) |
| **Wind** | United States Average | | 0.004 | |

## 8.6 Cooling Configuration and Boiler Type

As it was shown in Table 63, there are many configurations for power generation for each fuel type. So, information was collected to determine, as an average, the percentage of power that comes from each. In the United States 42.7 percent of power plants in the U.S. use once-through systems, 41.9 percent wet cooling towers, and 14.5 percent cooling ponds. These percentages were applied to each of the fuel types for which thermoelectric power had these choices. For coal-fired power plants, which have a boiler, 75% supercritical boilers and 25% subcritical were used based on projections made by the National Energy Technology Laboratory (Yen 2011). A summary of the assumptions for power generation category selection can be found below in Table 64.

Table 64: Configuration Percentages (Feeley Iii, Skone et al. 2008; Yen 2011)

| **Process** | |
|---|---|
| **Type** | **Percentage** |
| Once Through | 42.70% |
| Wet Cooling Towers | 41.90% |
| Cooling Ponds | 14.50% |
| **Coal Boilers** | |
| **Type** | **Percentage** |
| Supercritical | 75.00% |
| Subcritical | 25.00% |

## 8.7 Water Consumption for Energy Sources

Based on the information presented on Table 63 and Table 64, a water consumption value can be developed for each of the different fuel types as shown below in Table 65. As can be seen, using hydroelectric power consumes significantly more water than other energy sources. Nuclear power consumes the second most water. However, the water consumption values are averages for the U.S., so they do not take into account availability for a region, which may have plenty to spare and thus can use more water intensive processes. Rather than give specific water numbers, these water consumption values help to develop a trend and make a comparison to other phases for the life cycle of a vehicle. Depending on where the power comes from, it can significantly affect the total water consumption for a particular operation.

Table 65: Water Consumption for Energy Sources (Gleick 1994; Feeley Iii, Skone et al. 2008; Fthenakis and Kim 2010; Harto, Meyers et al. 2010; Yen 2011)

| Type | Water Consumption (l/kWh) |
|---|---|
| Coal | 0.871 |
| Natural Gas | 0.547 |
| Nuclear Power | 1.643 |
| Hydroelectric | 17.000 |
| Other (Solar) | 0.023 |

## 8.8 Energy Consumption for Production of Materials, Manufacturing of Parts, and Assembly

Now that the water consumption for the different energy sources has been calculated, the next step is to determine the actual energy consumption for the different phases. First, data was gathered from the paper that summarized all previous studies on energy consumption to date (Sullivan and Cobas-Flores 2001). All the data points were compiled for the spark ignited vehicles. Secondly, data from the Golf report was added because it was the only other report, separate from the published paper, recently written that examined the phases for the life of a vehicle (Schweimer and Levin 2000; Sullivan and Cobas-Flores 2001). The energy consumption data for the material production can be found below in Table 66. Three values are highlighted in red: the low value, the high value, and the average value calculated at the bottom. A comparison amongst all three is used to show how the water consumption can vary for each.

Table 66: Production of Materials Energy Consumption (Schweimer and Levin 2000; Sullivan and Cobas-Flores 2001)

| **Study** | **Material Production (MMBTU)** | **GJ** | **Sources** |
|---|---|---|---|
| Spark Ignited (1-A) | 44.4 | 46.8 | (Sullivan and Cobas-Flores 2001) |
| Spark Ignited (1B) | 53.5 | 56.4 | |
| Spark Ignited (2) | 36 | 38 | |
| Spark Ignited (3) | 31.8 | **33.5** | |
| Spark Ignited (5) | 68.3 | **72** | |
| Spark Ignited (7) | 67.3 | 71 | |
| Golf A4 1.4 | | 48 | (Schweimer and Levin 2000) |
| | **Average** | **52.3** | |

*In the article, SI denoted spark ignited. The number in the parenthesis is the case study.

The energy consumption data for the manufacturing of papers and assembly of the final vehicles was determined using the same approach as that of the material production shown below in Table 67. The same three values are highlighted in red. It should be noted that the manufacturing of parts and the assembly energy consumption were added together because of how they were presented in the published paper. As can be the seen, the production of materials consumes up to twice the energy when compared to the manufacturing and assembly stages put together.

Table 67: Manufacturing of Parts and Assembly Energy Consumption (Schweimer and Levin 2000; Sullivan and Cobas-Flores 2001)

| Study | Manufacturing & Assembly (MMBTU) | GJ | Sources |
|---|---|---|---|
| Spark Ignited (1-A) | 19.1 | 20.1 | (Sullivan and Cobas-Flores 2001) |
| Spark Ignited (1B) | 23.1 | 24.4 | |
| Spark Ignited (2) | 22.8 | 24 | |
| Spark Ignited (3) | 18.9 | **19.9** | |
| Spark Ignited (5) | 37.8 | **39.9** | |
| Spark Ignited (7) | 11 | 11.6 | |
| Golf A4 1.4 | | 37.6 | (Schweimer and Levin 2000) |
| | **Average** | **25.4** | **Sources** |

*In the article, SI denoted spark ignited. The number in the parenthesis is the study case.

### 8.9 Water Consumption in Energy

The U.S. Energy Information Administration database was reviewed to determine the percentage of energy source consumption for each of the fuel types as it applied to the various phases for the life of a vehicle. Their database contained the national average for energy source usage as of 2011. A summary can be found below in Table 68. Although much of the energy in the U.S. comes from coal-fired power plants, hydroelectric power has the biggest effect in the overall water consumption values.

Table 68: U.S. Average Energy Source (U.S. Energy Information Administration 2011)

| Energy Source | Percentage |
|---|---|
| Coal | 43.10% |
| Natural Gas | 24.20% |
| Nuclear Power | 18.60% |
| Hydro Electric | 8.30% |
| Other | 5.60% |

Using the percentages from Table 68 to calculate the power sources for the energy consumption from Table 66 and Table 67, the values for the types of energy consumed were calculated. The work of this thesis coupled these values with the water consumption for each data source, converting GJ to kWh, from Table 65, to determine the total water consumption for the material production, and the manufacturing of parts and assembly as shown in Table 69. The work of this thesis used the high, low, and average values for energy to calculate the values for water consumption. As can be seen, the water consumption related to energy consumption for the material production is significantly higher than that for manufacturing of parts and assembly. It can also be seen that these values are significant when compared to the water consumption for the other phases. A comparison of such will be made in a later section.

Table 69: Water Consumption for Different Phases (Liters)

| | **High** | **Low** | **Average** |
|---|---|---|---|
| Material Production | 44565 | 20749 | 32328 |
| Manufacturing & Assembly | 24664 | 12332 | 15693 |
| Total | 69229 | 33081 | 48020 |

Given the fact that hydroelectric power has such a big effect on the overall water consumption, different configuration was used, which may be more appropriate to areas where water is scarcer resource by replacing all of the hydroelectric power with other renewable power sources. The configuration can be found below in Table 70. Based on this configuration, the water consumption was calculated as shown in Table 71, which is significantly lower than the water consumption previously calculated. Changing the existing configuration for the other power sources would also have an effect on the overall water consumption but not as significant as changing the hydroelectric power.

Table 70: Other Energy Sources Configurations

| **Energy Source** | **Percentage** |
|---|---|
| Coal | 43.10% |
| Natural Gas | 24.20% |
| Nuclear Power | 18.60% |
| Hydro Electric | 0.00% |
| Other (Solar) | 13.90% |

Table 71: Water Consumption with Other Energy Configuration (Liters)

| | **High** | **Low** | **Average** |
|---|---|---|---|
| Material Production | 16348 | 7612 | 11859 |
| Manufacturing & Assembly | 9048 | 4524 | 5757 |
| Total | 25396 | 12136 | 17616 |

### 8.10 Second Assessment for Manufacturing and Assembly

After completing the first assessment, a different set of data points were used available from a report mentioned in section 4.6. The report had energy data for manufacturing and assembly operations. It included the complete life cycle energy consumption for these stages as shown below in Table 72. As can be seen, this energy consumption value is higher than the average from the previous data points but below the maximum. The main difference is that the energy sources are separated as electricity and fossil fuels. In other words, half the power that is consumed comes from electricity while the other half comes directly from fossil fuels, in this case natural gas.

Table 72: Additional Manufacturing and Assembly Energy Consumption (Sullivan, Burnham et al. 2010)

| | | | |
|---|---|---|---|
| **Total Energy (MJ)** | Fossil Fuels | 15,577 | 31,687 |
| | Electricity | 16,110 | |

Using the approach described earlier in section 8.4.9, the water consumption was calculated for the production of natural gas; the results shown in Table 73. Because the fuel was used directly in the operations no additional water is consumed in thermoelectric power plants.

Table 73: Water Consumption Natural Gas (Sullivan, Burnham et al. 2010)

| **Material** | **Natural Gas (m3)** |
|---|---|
| Quantity | 430.3 |
| MJ | 15,577 |
| kWh | 4327 |
| Water Consumption (liters) | 376 |

Using the power source configurations from Table 68 and Table 70, the water consumption was calculated for the electricity consumed from Table 72 as shown in Table 74. Although the energy consumption based on this report is higher than average, the water consumption is closer in value to that calculated using the alternative power source configuration for the first assessment. In other words, the inclusion of natural gas in the direct usage of energy, and the exclusion of the thermoelectric plants reduces the overall water consumption. Basically, the values in Table 71 for manufacturing and assembly are closer to the actual water consumption values because not all of the energy consumed comes directly from electricity. Some of the energy consumed in various operations on site comes directly from coal, or natural gas. A comparison of the magnitudes for the water consumption based on the different assumptions can be found below in Figure 42. This thesis will use the average value from Table 71 for both manufacturing and assembly and production of materials in future comparison of data for the water consumption among the different phases and the indirect water consumption based energy consumption. This will provide a median water consumption value for energy consumption that more closely resembles that from normal operations.

Table 74: Water Consumption for Second Assessment (Liters)

|  | **High** | **Low** |
|---|---|---|
| **Total Water** | 10,336 | 4,030 |

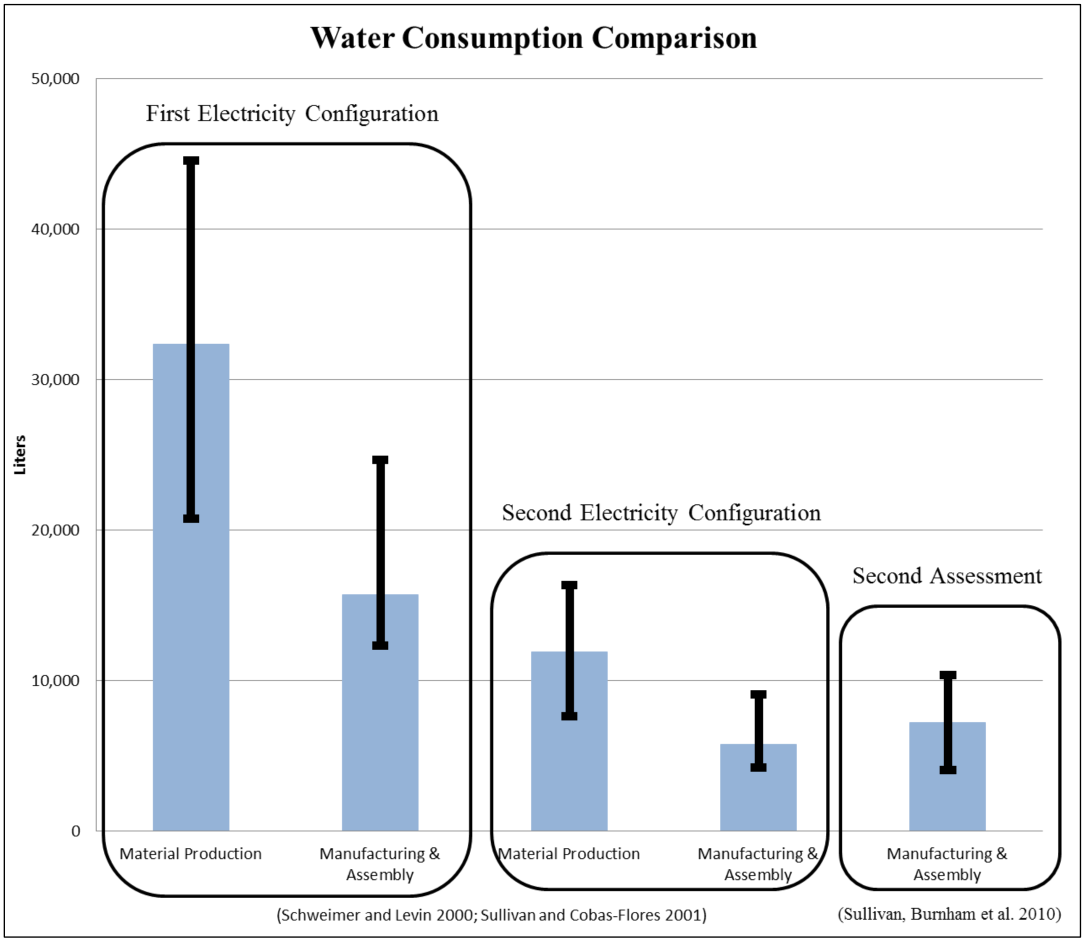


Figure 42: Water Consumption Comparison

# CHAPTER 9:

# CONCLUSION

## 9.1 Final Summary

This thesis quantifies the amount of water consumed in the production, use and recycling for a mid-sized gasoline powered US vehicle. Although water use is typically metered at the factory level, water consumption (i.e., water lost through evaporation and/or incorporation into a material, part, and/or product) is much harder to quantify and requires data on water discharge in addition to water input. As was shown, the difference can be an order of magnitude or more.

According to the analysis, 5,570 liters of water is consumed for the extracting and processing of materials to produce a typical US vehicle. The 5,570 liters is less than the approximately 10,000 liters reported in for the smaller Golf vehicles' material production, but is directionally in the same order of magnitude (Schweimer and Levin 2000). In comparison, water consumed for fuel production is almost 10 times more, namely, 52,000 liters for 160,000 km with a corporate average fuel economy of 11.7 km/liter gasoline. Water consumption in parts production was significantly less at 902 liters per vehicle with casting being the primary consumer of water. Vehicle recycling is relatively insignificant at 259 liters/vehicle. The assembly and production operations seem to be more significant than parts production, but the data reported by OEMs is very inconsistent and lack proper definition of use versus consumption. However, this thesis used 670 liters for my analysis because it represented the lowest reported water consumption and thus the best case scenario. The total life cycle water consumption based on the analysis can be found below in Table 75. A graphical representation of these values can be found in Figure 43.

Table 75: Life Cycle Water Consumption

| Life Cycle Phase | Water Consumption (Liters) | Percentage |
|---|---|---|
| Material Production | 5,569 | 9.38% |
| Parts Production | 902 | 1.52% |
| Vehicle Assembly | 670 | 1.13% |
| Use Phase | 51,965 | 87.53% |
| End of Life | 259 | 0.44% |
| Total | 59,365 | 100.00% |

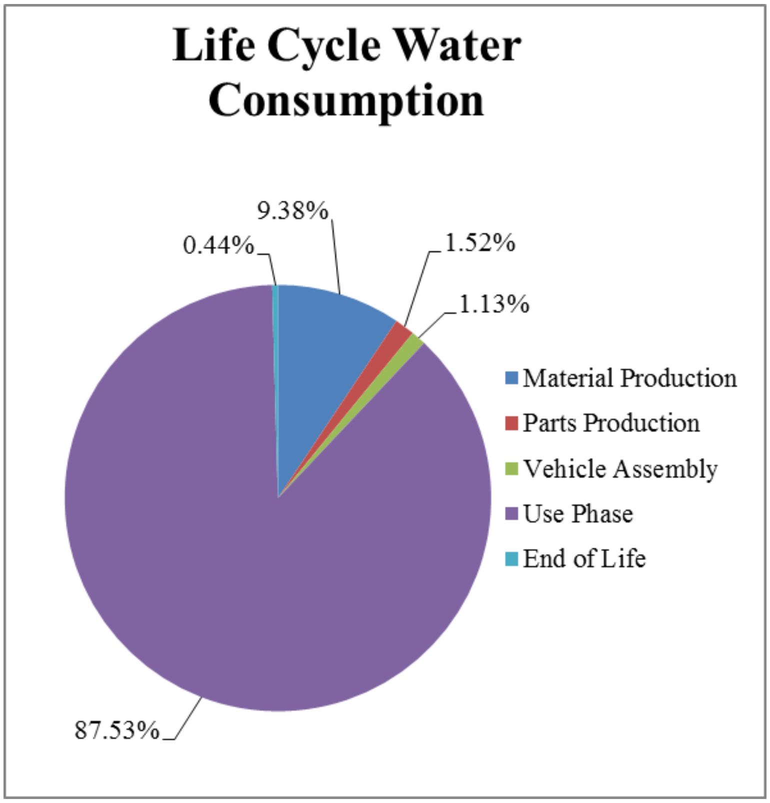


Figure 43: Life Cycle Water Consumption

Using water data found in the EcoInvent V2.2 database, this thesis calculated that 169,212 liters of water are used in the production of materials to produce one car. The comparison showed that the water numbers in the database were significantly (30 times) higher than those found in government documents, in published papers, and in publicly available company information. This can be explained by the fact that the EcoInvent water numbers only reflect water input data and do not include discharge or recycling rates.

Similarly, water for parts production processes using EcoInvent data was also significantly higher (35,000 liters) than the water consumption calculated using literature data (902 liters). Whereas the use phase dominated the life cycle in the water consumption assessment per literature data, the assessment using EcoInvent water data for gasoline production (and excluding turbine use water) resulted in a lower water amount than used for material productions. This would indicate that material production is more important than the use phase. Given the ambiguity of the water data in EcoInvent, such conclusion is to be questioned.

Overall, end of life recycling has a relatively low impact, ranging from 259 liter of water consumption (as per literature data) to 3,039 liters (as per EcoInvent data). Despite the variability and uncertainties still observed as part of this assessment, directional trends and areas of concern of the water consumption in a vehicle life cycle can be observed. A summary of the water use data from EcoInvent can be found below in Table 76.

Table 76: EcoInvent Data

| Stage | Water Use (Liters) |
|---|---|
| Material Production | 161,533 |
| Parts Production | 34,956 |
| Vehicle Assembly | 2,310 |
| Use Phase | 153,735 |
| End of Life | 3,039 |
| Total | 355,573 |

Table 77 compares the overall water input from the EcoInvent database as well as literature data discussed in this thesis. Figure 44 demonstrates the magnitude difference between water consumption and water use. For the most part, high levels of water recycling rates are seen in in all the phases. As can be seen, the material production actually has a higher value for water use than the use phase. As mentioned before, much uncertainty and ambiguity exists in the LCA databases and literature regarding water use and consumption data.

Table 77: Comparison of Water Consumption and Water Use

| Stage | Water Consumption (Liters) | Water Use (Liters) |
|---|---|---|
| Material Production | 5,569 | 161,533 |
| Parts Production | 902 | 34,956 |
| Vehicle Assembly | 670 | 3,390 |
| Use Phase | 51,965 | 153,735 |
| End of Life | 259 | 3,039 |
| Total | 59,365 | 355,573 |

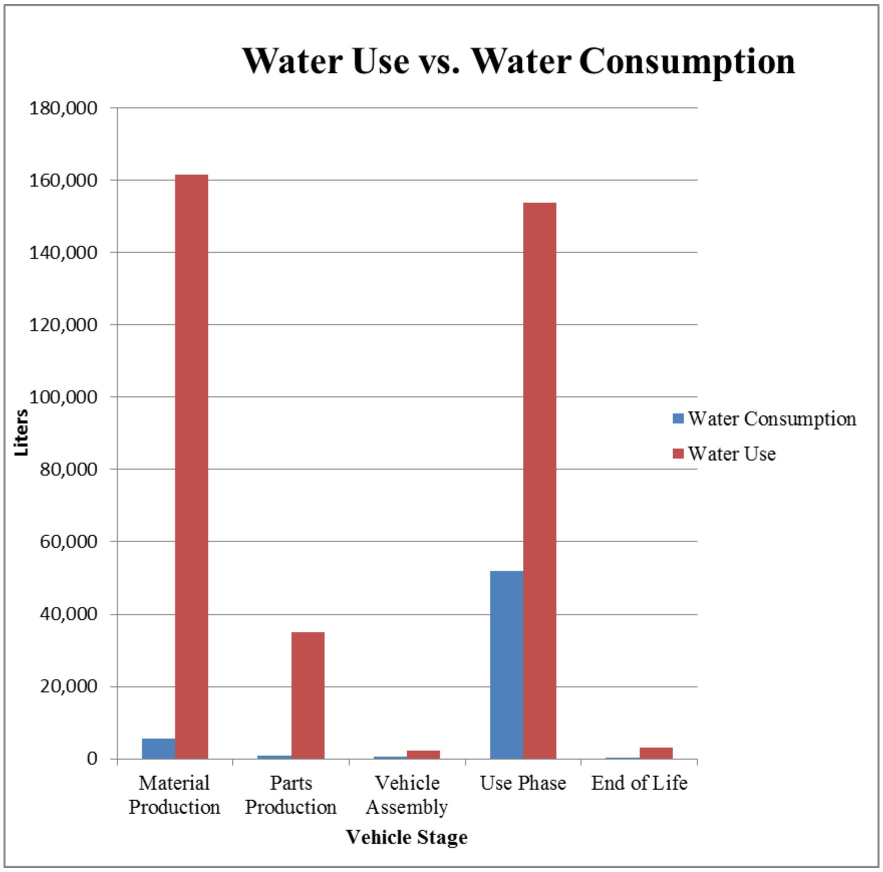


Figure 44: Comparison of Water Consumption and Water Use

Based on the work for each of the phases, we would only rely on EcoInvent database as a way to measure direct water intakes for the material production. The database had specific examples for plant production various materials which made their water intakes values realistic, although they were still somewhat higher than those presented in certain sustainability reports for total water intake (Alcoa 2007; Nippon Steel 2010; Alcoa 2012). The other phases tend to yield results which are not always consistent and may not match the direct water inputs as reported in industry reports. For instance, the end of life had two reports. One report provided water data for the disposal of a vehicle which included all processes. On the other hand, they also had another report that focused solely on the shredding of the vehicle whose water intake value was higher than the reported that included all processes for vehicle disposal.

## 9.2 Use Phase Water Consumption Magnitude Discussion

Based on the previous comparisons, it is clear that the use phase dominates the natural resource consumption for a vehicle. To better understand the causes for such high water consumption, further analysis were completed which is described in the following paragraphs.

One reason that the use phase may have such an enormous impact in the overall water consumption is that is requires the most materials out of all the phase for the life of a vehicle. In other words, in terms of inputs related to the life of a vehicle, the use phase requires the highest quantity of materials and therefore consumes the most natural resources.

An average gasoline powered midsize vehicle weights 1381 kilograms as explained in Table 2. Although it is composed of various materials, two main materials dominate the vehicle: ferrous metals and aluminum alloys. Ferrous metals, which can include cast iron, stainless steel, etc., make up 794 kilograms, or approximately 58 % of the vehicle. Aluminum alloys encompass 154 kilograms for a vehicle or approximately

12 % of a vehicle (Das, Curlee et al. 1995). Basically, ferrous metals and aluminum alloys can entail approximately 70 % percent of a vehicle and thus it can be assumed, as shown throughout the previous chapters that most of the natural resources consumed can be attributed to processing these two materials.

To determine representative water consumption value for ferrous metals and aluminum alloys, the analysis from this thesis added the total water consumption for the production of materials, the parts production, assembly, and end of life just these two types of metals and divided by their material weight found in the vehicle. This gives a general, simplified water consumption magnitude which can be compared to other materials. For ferrous materials, the water consumption was approximately 3.8 liters per kilogram. For aluminum alloys the water consumption was 16.2 liters per kilogram.

Table 51 shows that there is little difference in the water consumption for fossil fuels, which range from 3.8 to 10.0 liters of water per liter of fuel or 4.9 liters to 13.0 liters per kilogram, compared to ferrous metals and aluminum alloys. In fact, it would appear that processing aluminum has a much higher impact than the worst case scenario for fuel production even though most of the water consumption values for aluminum were conservative and included water recycling as shown in Figure 45. However, because 13,675 liters of fuel are consumed in the use phase as shown in Chapter 6, or 10,530 kg calculated using a density of 0.77 kg/liter, it significantly multiplies its effect. In other words, the use phase consumes the most water because it results in the highest amount of material inputs. In fact, based on this analysis, ferrous metals materials are 7.5 % while aluminum alloys are 1.5% by weight of the total material input seen in the use phase. An illustration of the total material input magnitudes for fuels, ferrous metals and aluminum alloys can be found below in Figure 46. Finding ways to reduce this material consumption would reduce the current trends in water consumption. This either can be accomplished by using more efficient technologies when processing fuels or by significantly increasing fuel efficiency.

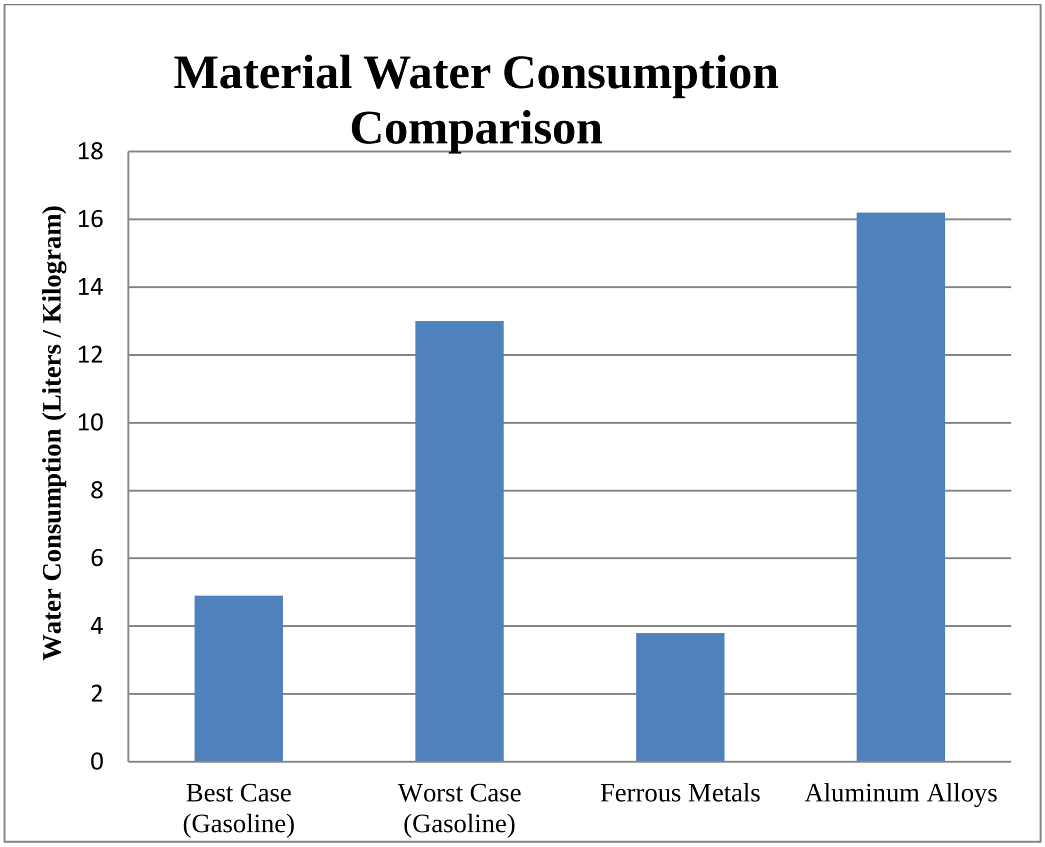


Figure 45: Water Consumption of Materials Comparison

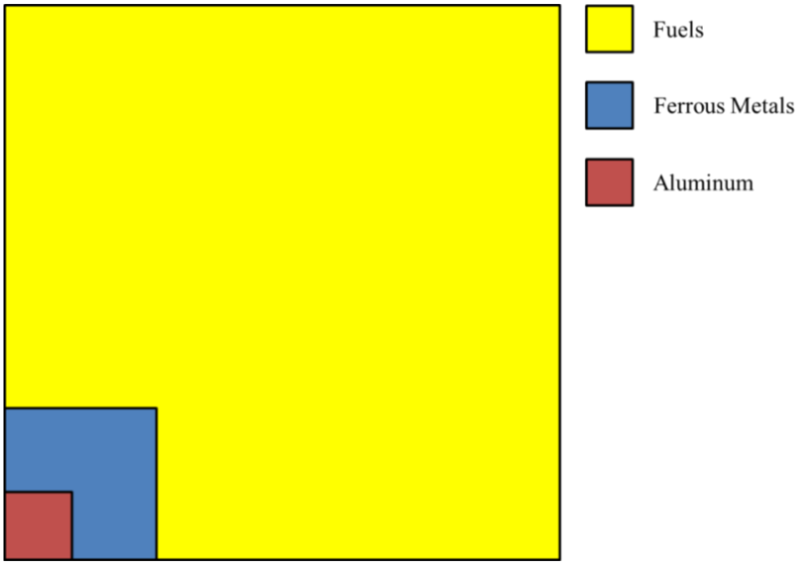


Figure 46: Material Input Percentage Comparison

## 9.3 Variability in Water Consumption

There is much variability in the data when determining the water consumption for the life of a vehicle so this analysis provides magnitudes and initial benchmarks that can serve as guidelines for future work. Specifically, there is much variability in the datasets for both the production of parts and the vehicle assembly. Depending on which assumptions are made throughout the calculations of these two values, the overall water consumption can vary greatly. Also, in the automaker's sustainability reports for instance, do not always include the scope of the work and report the terms "water use" and "water consumption" interchangeably. Consequently, it becomes difficult to identify the proper value. Even when sources use the proper terms, the data can often include water inputs that are not directly tied to the operations at hand such as water inputs for other operations like facility maintenance.

Based on the analysis presented in section 4.14 and 5.7, a slightly modified comparison can be developed as shown in Table 78. What can be seen is that the total water consumption is still in the same magnitude, at around 60,000 liters per vehicle. What is observed here is that the data contains ambiguities. It is likely that the automakers reports include actions beyond those of direct operations and potentially include things like facility maintenance and even other operations that may be counted as part of the supply chain in either the material production or parts production phase. It is also possible that the actual practices in the parts production phase include much more water intake and evaporation than it was actually calculated. This thesis focused on direct operations, so the act of cleaning the parts may make it necessary to include more water intake and thus more water evaporation. However, including this sort of data becomes in itself a fully variable set of calculations because of how different cleaning could be from one facility and operation to the next.

Table 78: Life Cycle Water Consumption

| Life Cycle Phase | Water Consumption (Liters) | Percentage |
|---|---|---|
| Material Production | 5,569 | 9.04% |
| Parts Production | 1,515 | 2.46% |
| Vehicle Assembly | 2,310 | 3.75% |
| Use Phase | 51,965 | 84.33% |
| End of Life | 259 | 0.42% |
| Total | 61,618 | 100.00% |

### 9.4 Comparison of Indirect Water Consumption and Direct Water Consumption

Based on the previous data for the water consumption for the life of a vehicle and the added indirect water consumption based on energy consumption, Table 79 was compiled. As can be seen, the indirect water consumption values are actually higher than all the water consumption in the life of a vehicle, with the exception of the use phase, combined. A graph was made to better represent the percentages of the total water consumption as shown in Figure 47. The water consumption for the production of materials is much higher than those of the other phases, with the exception of the use phase, for both the direct and indirect values. However, the difference between the indirect water consumption is much lower. This is because producing parts requires large amounts of energy for machining, forging etc. and thus consumes much more water in the production of that energy. The production of materials also requires a lot of energy, but requires more water for general processing directly.

Table 79: Direct and Indirect Life Cycle Water Consumption

| Stage | Water Consumption (Liters) | Percentage |
|---|---|---|
| Material Production | 5,569 | 7.23% |
| Parts Production | 902 | 1.17% |
| Vehicle Assembly | 670 | 0.87% |
| Total Use Phase | 51,965 | 67.50% |
| End of Life | 259 | 0.34% |
| Indirect: Material Production | 11,859 | 15.41% |
| Indirect: Parts & Assembly | 5,757 | 7.48% |
| Total | 76,981 | 100.00% |

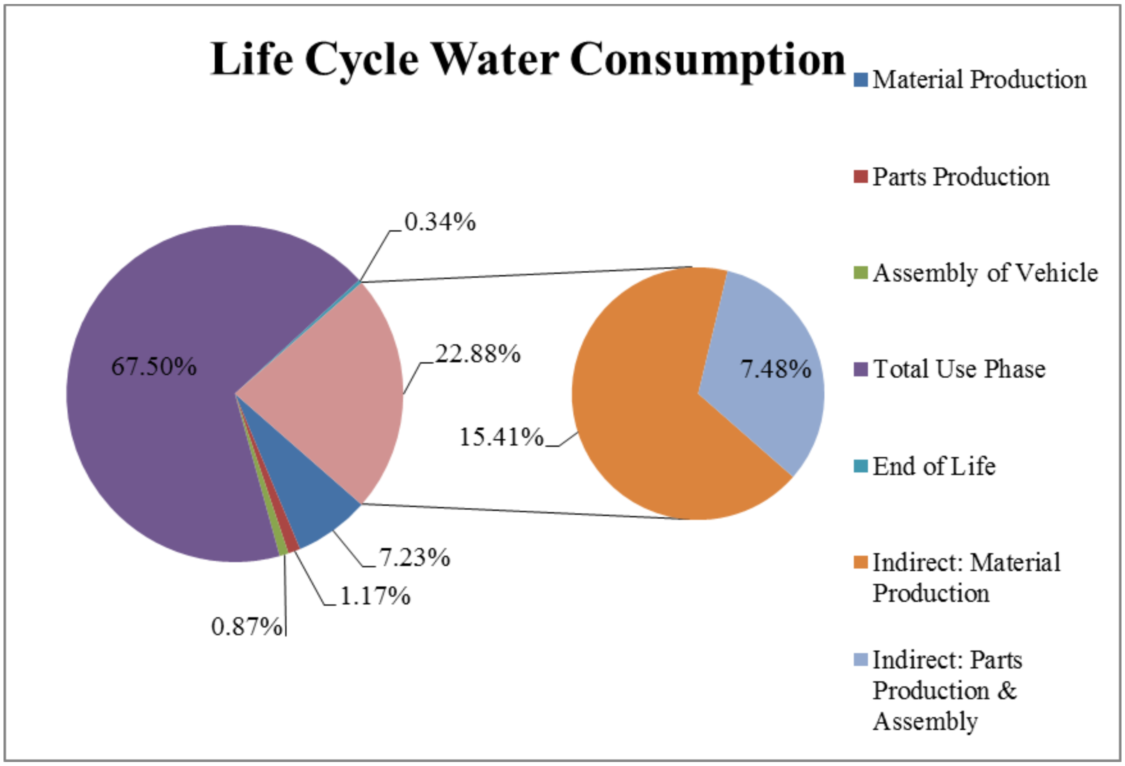


Figure 47: Water consumption for the Life of a Vehicle

### 9.5 Answer to Research Questions

At the beginning of the thesis, the issue of water scarcity, the importance of water use in manufacturing and the relevance of understanding water consumption in the life cycle of a vehicle were described. These topics lead to one major theme or question to be answered in this thesis:

| What is the water consumption for the life cycle of a passenger vehicle? |
|---|

Based on the analysis, the water consumption for the life of a vehicle was calculated to be 59,365 liters. However, the work of this thesis also discovered that there is much variability in the data and the assumptions by the references so this number, rather than being an absolute number, it is the representation of a magnitude or a benchmark to which future work can be compared. This thesis also showed that the water consumption could be higher, 61,618 liters per vehicle, if a different set of assumptions is made regarding the parts production and the vehicle assembly. The overall water consumption can significantly change depending on the assumptions for the data, which can include recycling rates, technologies being utilized, and region in which the water is being consumed. However, the thesis tended to select water consumptions values which were more conservative. In other words, this thesis tended to assume the best case scenarios and thus tended to find the data that would yield the lowest water consumption. The companies that recorded and provided their water input and water output data are more likely to be environmentally conscious and thus have an impact below the industry average.

In addition to the first question, this analysis was also trying to answer another question to determine not only the total value but also which areas for the life of a vehicle had the biggest water impact:

| What aspect of the life of a vehicle consumes the most water? |
|---|

By examining each of the phases, we determined that the processing of fuels during the use phase consumed the most water. Additionally, the work in this this thesis calculated the water consumption based on the energy consumption for the life of a vehicle. This value actually was bigger than all the water consumption for the phases for the life of a vehicle, excluding the use phase. In other words, the energy required to produce a vehicle actually consumes more water than the direct operations themselves. By reducing the energy consumption, automakers and their suppliers can actually also have lower environmental impacts in terms of water consumption. The analysis also found out that the energy mixture can significantly affect this value. In other words, the actual impact is highly localized and depends on the energy sources for each region. It remains to be seen as to what impact the water consumption base on energy production would have locally.

By comparing the energy consumption, carbon dioxide emissions and water consumption, one would see very closely related trends as shown Table 80. A graphical representation of the percentages for each can be found below in Figure 48. This thesis combined the use and maintenance phase based on the original study, and also added the parts production and assembly together from my analysis to make the comparison more direct. As can be seen, the use phase significantly dominates not just the energy consumption, but also the carbon emissions and the water consumption. The only minor difference lies in the parts production and automobile assembly for the water consumption. This value could be more closely related amongst the three different environmental factors had less conservative value for water consumption based on the automakers sustainability reports been chosen. The analysis could have also assumed recycling rates in the part productions that would result in a higher amount of water lost due to evaporation. It can also be seen that the end of life has a minimal effect on the overall natural resource consumption for the life of a vehicle. However, recycling material could reduce the overall impact of other phases, like material production, since there would be less processing required. Reducing the amount water intake at the use phase would significantly lower its impact. Although an increase in fuel efficiency would also play a role, it would not have such a high benefit on the overall water consumption as using more efficient methods of extraction and processing of fuels that use and consume less water.

Table 80: Water, Energy, and Carbon Dioxide Comparison

| **Stage** | **Water** | **Energy** | **Carbon** |
|---|---|---|---|
| Material Production | 9.38% | 8.40% | 7.10% |
| Parts & Automobile Production | 2.65% | 5.00% | 4.00% |
| Use Phase | 87.53% | 87.50% | 87.20% |
| End of Life | 0.44% | 0.10% | 0.40% |

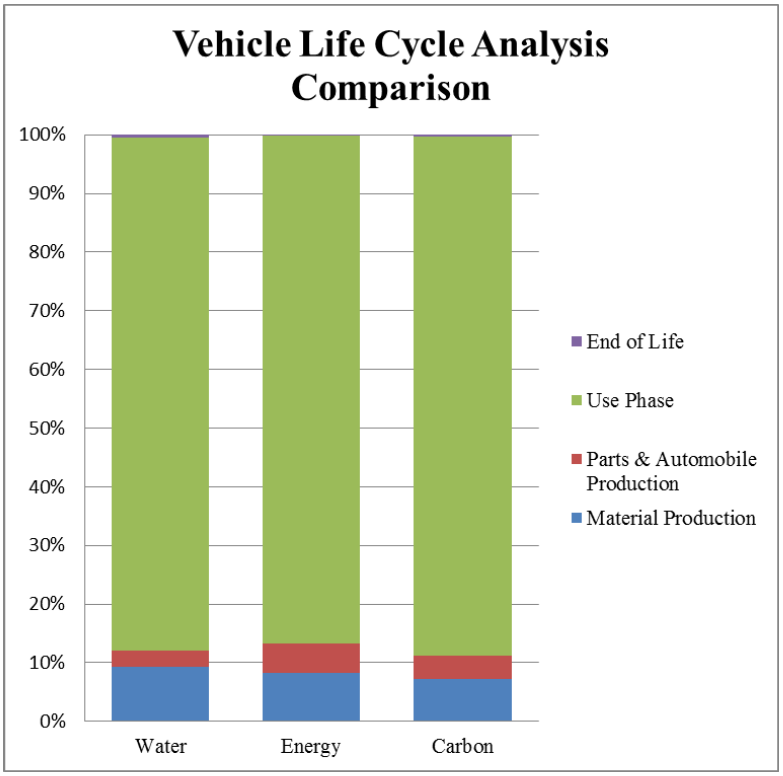


Figure 48: Vehicle Life Cycle Analysis Comparison

### 9.6 Reducing the Water Footprint

Based on the findings of our research, some basic recommendations can made to help reduce the overall water footprint of a vehicle for companies, the community, and even individuals. First and foremost, the fuel consumed in the use can be reduce through either more efficient vehicles, less driving, or better extraction practices that minimize water losses. Secondly, existing equipment can be upgraded to make sure that best available technology is being utilized or reorganize the flow of water within any given set of processes to help cool or clean as efficiently as possible. Focusing on the material production, specifically on steel and aluminum production would yield biggest savings. And lastly, efforts should be made to reduce the actual energy consumption within each of the operations for the automakers and their supply chains. Given the dependence on water for energy production, their overall impact can be reduced in a significant way by reducing energy consumption.

### 9.7 Vehicle Life Water Cost

Going beyond the possible environmental impact, using and consuming water throughout the life cycle of a vehicle can have added costs for companies. To calculate the water expense, we used two different sources for the cost of water and wastewater services based on Table 4 for Detroit, MI, and Table 5 for Pittsburgh, PA. Although this does not represent an exact value as different suppliers will be located throughout the U.S., or even in other countries, it does provide a magnitude benchmark to assess the cost of water for their operations. It also allows us to better understand where the highest costs are located throughout the life of a vehicle to identify areas where it would make sense to actively recycle water. We coupled the water costs from those cities with the water use, based on EcoInvent, and the water consumption, based on literature resources, from Table 77. The results of these calculations can be found below in Table 81 and Table 82. The tables show that the material production dominates the costs as it would be expected since they appear to have the highest water requirements, at, least according to EcoInvent. We also found that it would ultimately be more expensive to operate in Pittsburgh because of higher water costs.

Table 81: Life Cycle Water Cost Based on Detroit, MI

| Stage | Water Use (Liters) | Cost (USD) | Water Consumption (Liters) | Water Output (Liters) | Cost (USD) |
|---|---|---|---|---|---|
| Material Production | 161,533 | $84.71 | 5,569 | 155,964 | $203.51 |
| Parts Production | 34,956 | $18.33 | 902 | 34,054 | $44.44 |
| Vehicle Assembly | 2,310 | $1.21 | 670 | 2,720 | $2.14 |
| Use Phase | 153,735 | $80.62 | 51,965 | 101,770 | $132.80 |
| End of Life | 3,039 | $1.59 | 259 | 2,780 | $3.63 |
| Total | 355,573 | $186.47 | 59,365 | 296,208 | $386.51 |

Table 82: Life Cycle Water Cost Based on Pittsburgh, PA

| Stage | Water Use (Liters) | Cost (USD) | Water Consumption (Liters) | Water Output (Liters) | Cost (USD) |
|---|---|---|---|---|---|
| Material Production | 161,533 | $325.16 | 5,569 | 155,964 | $105.89 |
| Parts Production | 34,956 | $70.37 | 902 | 34,054 | $23.12 |
| Vehicle Assembly | 2,310 | $4.65 | 670 | 2,720 | $1.11 |
| Use Phase | 153,735 | $309.47 | 51,965 | 101,770 | $69.09 |
| End of Life | 3,039 | $6.12 | 259 | 2,780 | $1.89 |
| Total | 355,573 | $715.77 | 59,365 | 296,208 | $201.10 |

A few important observations can be made based on the previous results. For automakers, the decision whether to save or not water may not necessarily be directly linked to costs; personnel wages and energy consumption may cost companies significantly more. Improvements in their water usage may have a more positive effect on their image and also allow them continued access to the necessary water for their operations. For producers of fuel, the cost of water appears to be minimal, especially when comparing it to the high prices of fuel we are currently seeing and the high production rates of their applications. This appears to be the case if we use the EcoInvent database as a reference for their water intake. Their decision to include water recycling technologies may be more motivated by government regulations and expectations from surrounding communities. For producers of raw materials, however, the decision to introduce water recycling technologies may actually have economic drivers.

Given the high cost of water associated with material production, we decided to go a step further and calculate the actual costs associated with the production of the steel and aluminum. Again, we used the costs of water and wastewater services for Detroit and Pittsburgh. We coupled that with the EcoInvent water data from Table 18. The results of these calculations can be found below in Table 83 and Table 84. The relevance of incorporating water recycling technologies becomes more apparent when we consider the cost of carbon steel and aluminum in the world which are $ 0.812 and $2.16 dollars ($0.98 / lb.) per kilogram (InfoMine Inc. 2012; worldsteelprices.com 2012). In other words, given said parameters, the cost of water could account for 18-48 % of the total costs of production for steel and 16-42% for aluminum which explains why companies like Nippon Steel and Alco are already recycle between 90-95% of the water they use in their operations, losing the rest to evaporation (Alcoa 2007; Nippon Steel 2010). It is, however, likely that given the high usage of water for their operations, they may have special permits which allows them to withdraw water from a river, rather than obtain clean, potable water directly from the city at a reduce cost (Alcoa 2007). It is also possible that the water inputs associated with EcoInvent are not as high as those seen by material producers. So, in essence, their costs may not be as high as those presented here. These calculations serve to demonstrate the important of recycling water in material production, which, in terms of the life cycle of a vehicle, appears to have the most financial incentives to reuse water.

Table 83: Water Costs Associated with Material Production in Detroit, MI

| Material | **Steel** | **Aluminum** |
|---|---|---|
| EcoInvent (Liters/Kg) | 86 | 203 |
| Cost of Water (USD) | $0.05 | $0.11 |
| Water Consumption (Liters) | 2.89 | 13 |
| Water Output (Liters) | 83.11 | 190 |
| Sewage Costs (USD) | $0.11 | $0.25 |
| Total Cost | $0.15 | $0.35 |

Table 84: Water Costs Associated with Material Production in Pittsburgh, PA

| Material | **Steel** | **Aluminum** |
|---|---|---|
| EcoInvent (Liters/Kg) | 86 | 203 |
| Cost of Water (USD) | $0.17 | $0.41 |
| Water Consumption (Liters) | 2.89 | 13 |
| Water Output (Liters) | 83.11 | 190 |
| Sewage Costs (USD) | $0.21 | $0.49 |
| Total Cost | $0.39 | $0.90 |

The relevance of incorporating water recycling technologies becomes more apparent when we consider the cost of carbon steel and aluminum in the world which are $ 0.812 and $2.16 dollars ($0.98 / lb.) per kilogram (InfoMine Inc. 2012; worldsteelprices.com 2012). In other words, given said parameters, the cost of water could account for 18-48 % of the total costs of production for steel and 16-42% for aluminum which explains why companies like Nippon Steel and Alco are already recycle between 90-95% of the water they use in their operations, losing the rest to evaporation (Alcoa 2007; Nippon Steel 2010). It is, however, likely that given the high usage of water for their operations, they may have special permits which allows them to withdraw water from a river, rather than obtain clean, potable water directly from the city at a reduce cost

(Alcoa 2007). So, in essence, their costs may not be as high as those presented here. These calculations serve to demonstrate the important of recycling water in material production, which, in terms of the life cycle of a vehicle, appears to have the most financial incentives to reuse water.

In summary, the decision behind recycling water may not entirely be driven by the desired to save money. For certain applications, the production of materials, which require high flow rates of water, it may actually be economically feasible to introduce new technologies as a way of reducing costs. On the other hand, automakers and gasoline producers may not necessarily have a reasonable payback period on their investments to recycle water. However, this is not to say that they should not make an effort to reuse water and reduce waste. It is less quantifiable to measure the impact of their relations with the surrounding communities is they are misusing resources and causing havoc during their operations. This could result in a disconsolation of their operations by new legislative regulations created by the communities, or may incite a series of fines as a way to motivate companies to reduce their waste.

## 9.8 Uncertainty

It is clear that further research is needed before any robust conclusions on life cycle water consumption can be drawn. The data uncertainty is still very significant and definitions/system boundaries of the different literature sources are not fully consistent. It was a very common practice to use the term “water consumption” and “water use” interchangeably for many of the data sources so care was taken to separate the two.

Most of the data presented in the thesis illustrates the use of the best available technology by U.S. standards. Most of the information found was based on the U.S. industry which must meet certain EPA environmental regulations so the use of wastewater recycling seemed a common trend. This trend may not exist in other localities such as low cost countries, however, where many automotive suppliers reside. This may mean that the actual water “splash” from materials production or parts production may be higher than stated in this thesis. A manufacture may actually have much higher water consumption if they don’t recycle water or if their practices are wasteful.

## 9.9 Future Work

The work of my thesis serves as an initial benchmark as no previous research had been completed to determine the water consumption for the life of a vehicle, let alone for most other products. Given more time, this thesis would continue to investigate for more data, especially in the parts production, since there is so much variability amongst the different vendors and suppliers. Most of the data presented in the thesis is based on U.S. data, so it would be interesting to examine other countries to better understand how their regulations and practices affect the overall water consumption.

Going beyond a water inventory (in terms of consumption and/or use) for various vehicle types and models, the next step is to assess the actual impact. The impact of water consumption varies by region and locality, and a differentiation would be needed whether the water consumption actually happens in water scare regions or not. This could entail examining the environmental, economic, and social aspects of the water consumption associated with the communities surrounding these operations.

In addition, the quality of water (input and output) is important: obviously the consumption of drinkable water in water scarce regions is much more important than the consumption of non-drinkable water. Understanding the effect of quality of the water that is discharged was not examined. Simply using the water, and returning most of it to its original sources may not be enough if many contaminants are being added with each operation.

It remains to be seen whether a life cycle approach – adding up generic figures along the life cycle – is the right approach. For all these reasons, care and caution should be taken when using pure total figures of water consumption or water use. Establishing water consumption in this matter may only be applicable as a general initial benchmark. More meaningful interpretations may require the examination of the effects and quality of this water and the effects of such.

# APPENDIX A

# STEEL

This appendix provides a detailed description of the process of making steel including where and how water is consumed in the various processes.

## A.1 Cokemaking

In cokemaking, coal is heated to high temperatures in an oxygen deficient atmosphere to remove the volatile components. The remaining residue is coke, an efficient reductant for blast furnace iron making. Almost all coke for the integrated iron and steel industry is manufactured using the byproduct process. Byproduct coke ovens permit coal during the coking process. Coking is carried out in narrow, rectangular refractory brick ovens arranged in groups of up to 100 ovens known as batteries. The ovens consist of coking chambers, heating flues, and regenerative chambers. The coking chambers in a battery alternate with heating chambers; regenerative chambers are located underneath. Pulverized coal is charged into the ovens through openings in the top. The necessary heat for distillation of the volatile components is supplied by external combustion of recovered coke oven gas, blast furnace gas, and natural gas through flues located between ovens. When the coking cycle is completed, doors on both ends of the oven are removed and the coke is pushed out into a quenching car and transported to a quenching tower, where water is sprayed onto the coke mass to cool it. The coke is subsequently sized and sent to the blast furnace or to storage (Margolis and Brindle 2000).

The largest volume of water used in coke plants is for non-contact cooling in a variety of cooling and condensing operations with a process flow of up to 900 gallons per ton (Ellis, Dillich et al. 2000; Margolis and Brindle 2000). Although the best technology can recycle final cooler water, consumption of water for the coke quenching can still be

120 gallons per ton of coke. The typical volume of process wastewaters generated at a well-controlled coke plant is approximately 100 gallons per ton of coke produced (Margolis and Brindle 2000). So, the total water consumed is 220 gallons per ton or 0.83 liters per kilogram.

## A.2 Iron Making

In blast furnace iron making, the iron ore is reduced by removal of the oxygen, and the resulting iron is melted. In the process, coke, natural ore, pellets, sinter, briquettes, nodules and other agglomerated products are consumed to make iron. Agglomeration processes such as pelletizing produce coarse particles of suitable size for charging into the blast furnace. In pelletizing, an unbaked ball or "green" pellet is formed from iron ore concentrate combined with a binder. The green pellets are then hardened by heat treatment in an oxidizing furnace. The major pelletizing systems are the traveling grate, the shaft furnace, the grate kiln, and the circular grate. Pelletizing is almost always done at the mine site rather than at the mill. From the mine, the pellets are transported by boat or railroad to the mill, where they are fed into the blast furnace along with coke, fluxes, and often sinter. In addition to pelletizing, the other major agglomeration process for preparing ore for charging into the blast furnace is sintering. Sintering is a process that converts natural fine ores, ore fines from screening operations, water treatment plant sludges, air pollution control dusts, and other iron-bearing materials of small particle size into a clinker-like agglomerated product. Sintering enables a mill to recycle iron-rich material such as mill scale and processed slag back into the iron making process. The raw materials are placed on a continuous, traveling grate called the sinter strand. At the beginning of the strand, the coke breeze in the mixture is ignited by gas burners, which leads to surface melting and agglomeration of the bed. On the underside of the strand are windboxes that pull combustion gases down through the material bed into a duct leading to gas cleaning equipment. The bed temperature is hot enough to sinter the fine ore particles together into porous clinkers. The fused sinter mass is cooled, crushed, screened, and sent to be charged along with ore to the blast furnace. (Margolis and Brindle 2000).

The main uses of water in a sintering plant are for controlling the moisture content of the pre-sinter mix, for dust control, and for sinter produce cooling. Wastewaters, typically 120 gallons per ton of sinter, are generated from the wet air pollution control devices on the windbox and discharge ends of the sinter machines. Either electrostatic precipitator or wet venturi-type scrubber technology is typically used for dust control. Wastewater treatment comprises sedimentation for removal of heavy solids; recycle of clarifiers or thickener overflows, and metals precipitation treatment for blowdowns. Some sinter plants are operated with once-through treatment (Margolis and Brindle 2000).

Blast furnaces are used to produce pig iron. In the liquid form the pig iron is generally referred to hot metal. The blast furnace is a tall, shaft-type furnace with a vertical stack superimposed over a crucible-like hearth. Iron ore, coke, sinter and fluxare fed into the top of the blast furnace; heated air, typically augmented with gaseous, liquid, or powdered fuel, is injected into its base. The production of one net ton of iron requires approximately 1.5 tons of ore or other iron bearing material, 0.22 tons of sinter, and 0.55 tons of coke. As the charge materials descend through the furnace, reducing gas generated by the burning coke flows upward, converting the iron oxide in the ore to iron. The coke also provides the structural support for the unmelted burden materials. The combustion of the coke generates sufficient heat to melt the iron, which accumulates in the bottom of the furnace. The major function of the flux is to combine with unwanted impurities such as ash in the coke and gangue in the ores to make a drainable fluid slag. The operation of a blast furnace is a continuous process, and the furnace continues to produce liquid iron and slag as long as it is in operation. The iron and slag that accumulate in the hearth are removed at regular intervals through tapholes located slightly above the floor of the hearth. The molten iron is tapped into refractory-lined cars for transport to the furnace. (Margolis and Brindle 2000).

The blast furnace is one of the largest water users in an integrated mill. The main water use is for non-contact cooling of various parts of the furnace and auxiliaries. Additional water is used for furnace moisture control, dust control, and slag granulation. Contact water use is primarily associated with blast furnace gas cleaning operations necessary to recover the fuel value of the off gas. Nearly all of the wastewater generated from blast furnace operations is direct contact water used in the gas coolers and high energy scrubbers used to clean the blast furnace gas. Typical water requirements are 6,000 gallons per ton of iron. Standard treatment includes sedimentation in thickeners or clarifiers, cooling with mechanical draft cooling towers and high-rate recycle. Existing technology is able to recycle 98% of the water used in a typical blast furnace (Margolis and Brindle 2000). A summary of the water consumption for this part of the steel making process can be found in Table 85. The ratio of raw materials needed to make the product is shown in Table 86.

Table 85: Iron making (Margolis and Brindle 2000)

| **Process** | **Water Consumed (Gallons / Ton)** | **Water Consumed (Liters / Kg)** |
|---|---|---|
| Gas cooling water and scrubber water for gas cleaning | 120 | 0.45 |
| Sinter | 120 | 0.45 |

Table 86: Ratio of raw materials (Margolis and Brindle 2000)

| Process | Tons use per ton of Iron |
|---|---|
| Coke | 0.55 |
| Sinter | 0.22 |

### A.3 Electric Arc Furnace

Electric arc steelmaking furnaces produce carbon and alloy steels from scrap metal along with variable quantities of direct reduced iron, hot briquetted iron, and cold pig iron. Hot metal may also be added if available. The feed or charge is melted in cylindrical, refractory-lined electric arc furnaces equipped with carbon electrodes that are lowered through the furnace roof. During charging, the roof is removed and the scrap metal and other iron-bearing materials are placed into the furnace. Alloying agents and fluxes are added through doors on the side of the furnace. The electrodes are lowered into the furnace to about an inch above the metal and current is applied, generating heat to melt the scrap. (Margolis and Brindle 2000).

Although electric arc furnaces can have a significant non-contact cooling water requirements, few furnaces have significant process wastewater discharges. Most electric arc furnaces are operated with dry air cleaning systems with no process wastewater discharges. Other non-contact water applications include water-cooled ductwork, roof, sidewalls, doors, lances, panels, cables, and arms. These systems usually incorporate evaporative cooling towers or closed cooling loops. A small number of wet and semi-wet air cleaning systems also exist. The water flows for those systems with wet and semi-wet air cleaning systems are about 2,100 gallons/ton. The best available technology is assumed to be clarification and recycle of wet air emission control scrubber water, and subsequent sludge dewatering reduces the final consumption to 110 gallons per ton or 0.42 liters per kilogram (Margolis and Brindle 2000).

## A.4 Refining

Ladle metallurgical furnace processes are used to further refine the molten steel from the electric arc furnace prior to casting. These processes include reheating, refining, inclusion modification, and degassing. Reheating of the steel using arc reheating or oxygen injection permits adjustment of the steel temperature to levels needed for uninterrupted sequential casting (Margolis and Brindle 2000).

Of all the refining processes, only vacuum degassing uses process water and generates effluent streams. Vacuum degassing involves direct contact between gases removed from the steel and condenser water. Applied water rates for vacuum degassing are typically around 1,250 gallons per ton of steel. Standard treatment includes processing the total recirculating flow or a portion of the flow in clarifiers for TSS removal, cooling with mechanical draft cooling towers, and high-rate recycle. Blowdowns are usually co-treated with steelmaking and/or continuous casting wastewaters for metals removal. Vacuum degassing plants are often operated as part of ladle metallurgy stations where additional steel refining is conducted. Using the best available technology economically available vacuum degassing is assumed to be sedimentation and recycle 98% for condenser contact cooling waters resulting in a water consumption of 25 gallons per ton or 0.09 liters per kilogram (Ellis, Dillich et al. 2000; Margolis and Brindle 2000).

## A.4 Casting

In continuous casting, the molten steel is solidified into a semi-finished shape for subsequent rolling in the finishing mill. Continuous casting eliminates the need for classical processes such as teeming into ingots; mold stripping; reheating; and primary hot rolling into semi-finished shapes. The continuous process has higher yields, quality, and productivity versus the ingot process, as well as higher energy efficiency. In the continuous casting process, molten steel is delivered in ladles and poured into a reservoir from which it is released into the mold of the casting machine. The steel cools as it passes through the mold and forms a solid outer shell or "skin." As the steel proceeds onto the runout table, the center of the steel also solidifies, yielding a semi-finished shape at a specified width and thickness. Depending on the type of caster used, various shapes are produced (Margolis and Brindle 2000).

Continuous casters usually include several separate closed-loop cooling water systems. Water use is categorized by function in the casting process: primary (mold), secondary (spray), and auxiliary (equipment). The primary cooling process is the non-contact cooling of the molten steel shell in the mold. Closed-loop, non-evaporative cooling is primarily employed when high surface and strand quality are required. Secondary or spray cooling occurs as the strand exits the mold, with contact water sprays covering the surface of the strand. Auxiliary cooling is non-contact or internal cooling of the casting equipment. Direct contact water systems are used for spray cooling. Applied water rates for the contact systems are typically about 3,600 gallons per ton of cast product. Wastewater treatment includes settling basins for scale recovery, oil skimmers, straining devices, mixed- or single-media filtration, and high-rate recycle. As with other contact systems, this system will typically utilize evaporative tower systems for cooling. For continuous casting, the BPT limitations assume closed loop cooling for the casting machine and a mold cooling water system; and sedimentation, filtration, cooling, and recycle 98% for spray water resulting in a water consumption of 72 gallons per ton or 0.27 liters per kilogram (Margolis and Brindle 2000).

## A.5 Forming and Finishing

After casting, the slabs, billets, and blooms are further processed to produce strip, sheets, plate, bar, rod, and other structural shapes through various hot forming operations, which are sometimes followed by cold forming operations depending on the final product. Prior to hot forming, the semi-finished shape must first be heated to rolling temperatures in a reheat furnace. The most common hot forming process is hot rolling, where a heated steel slab is passed between two rolls revolving in opposite directions. Each set of rolls produces an incremental reduction in thickness in the slab. A hot strip mill typically contains a roughing mill, where initial reduction is achieved. Surface scale is removed from the heated slab by a scale breaker and water sprays prior to entering this mill. At the end of the roughing section, the steel enters the finishing mill for final reduction, after which it is cooled and coiled or slit. Steel that has been hot-rolled and pickled may be cold rolled to make a product thinner and smoother, suitable for a variety of uses from car bodies to tin cans. Cold rolling hardens the steel, which must then be heated in an annealing furnace to make it more formable (Margolis and Brindle 2000).

In hot rolling operations water is used for direct cooling of mill stand work rolls and descaling of steel prior to rolling. Descaling is a finishing process removes heavy scale from selected specialty and high-alloy steels. Typical process wastewaters from finishing operations include rinses and spent concentrates from alkaline cleaners, pickling solutions, plating solutions, and electrochemical treating solutions. Descaling wastewaters originate from quenching and rinsing operations conducted after processing in the baths. Descaling wastewaters are usually co-treated with wastewaters from other finishing operations. Water use and discharge rates from hot forming operations vary greatly depending upon the type of hot forming mill and the shapes produced. Although water used during hot forming can be up to 6,000 gallons per ton during quenching and 1,800 gallons per ton during descaling, using the best economically achievable technology, can be recycled and only have a consumption rate of 260 galls per ton of steel or 0.98 liters per kilogram (Ellis, Dillich et al. 2000; Margolis and Brindle 2000).

Water is also used in finishing operations like pickling and cold reduction primarily as non-contact cooling water, solution makeup, and rinse water. Non-contact cooling typically incorporates evaporative cooling towers or closed-loop systems. Process wastewater from cold forming operations results from using synthetic or animal-fat based rolling solutions and can be 10 gallons per ton for mills with recirculated rolling solutions. Although water usage can be up to 1,000 gallons per ton, typical water consumption for pickling is assume to be 20 gallons per ton because certain limitations assume recycle of fume scrubber waters, metals precipitation, and sludge dewatering. Cooling and descaling water is normally discharged from the mill into scale pits where the heavier solid particles settle out. The semi-cleaned water is typically sent on to a treatment plant containing straining devices, solids removal, and/or deep bed filtration to remove fine particulate (Margolis and Brindle 2000). The total water consumption

# APPENDIX B

# ALUMINUM

This appendix provides a detailed description of the process of making aluminum including where and how water is consumed in the various processes.

## B.1 Alumina Production

Alumina production often takes place near bauxite mines. Approximately 98% of the alumina produced worldwide is manufactured via the Bayer process, which consists of digestion and calcination. Initially, the bauxite is washed and ground. During digestion, the bauxite is dissolved in caustic soda at high pressure and at high temperature. The resulting liquor contains a solution of sodium aluminates and undissolved bauxite residues containing iron, silicon, and titanium. These residues sink gradually to the bottom of the tank and are removed. They are known as red mud. The clear sodium aluminate solution is pumped into a huge tank called a precipitator. Aluminum hydroxide is added to seed the precipitation of aluminum hydroxide as the liquor cools. The aluminum hydroxide sinks to the bottom of the tank and is removed. It is then passed through a rotary or fluidized calciner to drive off the chemically combined water. The result is alumina, a white powder (Schwarz 2004). The Bayer process requires a considerable amount of process water for washing and filtering the red mud and the alumina. Water is used during fine residue separation, and for washing as part of the classification stage. Typical process water consumption 4590 kg for metric ton of alumina or 4.95 liters per kilogram (Margolis and Sousa 1997).

## B.2 Anode Production

The electrolysis of aluminum oxide to form aluminum relies in the application of electric current to separate oxygen from the aluminum. An electrolysis process requires an anode and a cathode. The production of anode net water consumption of water is

3,215 kg of water per metric ton of anode or 3.22 liters per kilogram, mostly in the wet plant wet air pollution control and to cool green anode blocks to prevent them deforming (Margolis and Sousa 1997).

## B.3 Aluminum Production

The basis for all primary aluminum smelting plants is the Hall–He´roult process. Alumina is dissolved in an electrolytic bath of molten cryolithe inside a large carbon- or graphite-lined steel container known as a pot. An electric current is passed through the electrolyte at low voltage and at very high amperage. The electric current flows between a carbon anode, and a cathode, formed by the thick carbon or graphite lining of the pot. The anodes are used up during the process then they react with the oxygen from the alumina. Molten aluminum is deposited at the bottom of the pot and is siphoned off periodically (Schwarz 2004). This process uses very little water. The typical consumption is .0009 kg / metric ton used during cleaning in the form of a wet scrubber (Margolis and Sousa 1997).

## B.4 Secondary Aluminum Production

Secondary production consists of two process steps: scrap preparation, mixing, and charging, on the one hand, and the processes within the remelter/refiner (remelting, refining, and salt slag preparation), on the other hand. Scraps recovered are treated according to their quality and characteristics. Common treatment processes are sorting, cutting, baling, or shredding. Free iron is removed by magnetic separators. The different scrap types are selected and mixed in such a way that their chemical composition is as close as possible to that of the required alloy (Schwarz 2004). Depending on the type of scrap and the desired product quality, different types of furnaces for melting aluminum scrap are used. Scrap for the production of casting alloys is commonly melted in rotary furnaces under a layer of liquid melting salt. A company producing casting alloys from old and new scrap is commonly called a refiner. Producers of wrought alloys prefer open hearth furnaces in varying designs. These furnaces are normally used without salt. Wrought aluminum from mainly clean and sorted wrought alloy scrap is produced in a remelter. The alloy production in rotary furnaces is followed by a refining process. The molten alloy is fed into a holding furnace (converter) and purified through the addition of refining agents. After the melting process, the liquid melting salt used in rotary furnaces is removed as salt slag. In the past, the salt slag was land filled. Today, the salt slag is prepared as a rule. The aluminum and the salt within the salt slag are recovered (Schwarz 2004). Typical water consumption is 320 kg / metric ton of aluminum consumed or 0.32 liters per kilogram. Water is mostly used for air pollution control (Margolis and Sousa 1997).

## B.5 Semi-Fabrication: Casting

After alloying, the molten primary or secondary aluminum undergoes some combination of casting, hot rolling, cold rolling, drawing, extruding, etc. The molten aluminum is either cast in ingots or it is continuous fed and cast to a rolling mill. The primary use of water in the cast house is for cooling of molten aluminum as it is formed in the casting process. In refining and casting, process water is required to make up for the evaporative losses from the cooling water system. The net water consumption for primary ingot casting is typically 10,800 Kg per metric ton of aluminum or 10.8 liters per kilogram. For secondary casting, the water consumption is 320 kg for metric ton. One explanation for the large difference between the two is that most primary plants use on through water, whereas secondary plants can be coupled to mills where all process water is recycled several times (Margolis and Sousa 1997).

# APPENDIX C

# POLYUTHERANE

This appendix provides a detailed description of the process of making polyurethane, including where and how water is consumed in the various processes.

## C.1 Chemical Reaction

Polyurethane is sometimes abbreviated to PU or PUR. The range of polyurethane types, from flexible or rigid lightweight foams to tough, stiff elastomers, allows them to be used in a wide diversity of consumer and industrial applications. Some examples are: rigid foam, flexible foam (automotive seating), integral skin, semi-rigid and low density structural foams (steering wheels, headrests and other automotive interior trim components), and elastomers (vehicle body panels). The acronym MDI was devised from one of the chemical's many names, methylene diphenyl diisocyanate. The acronym TDI comes from several synonyms for TDI, the commonest of which is toluene diisocyanate (Allport 2003).

The basic reaction between a diisocyanate and a polyol produces a polyurethane addition polymer with the liberation of heat (Allport 2003).

diisocyanate + polyol ——→ polyurethane polymer + heat (Allport 2003)

However, a number of ancillary chemicals and processing aids are usually required to allow sufficient control to produce useful commercial products. Catalysts are needed to allow the reaction to progress at a speed compatible with production processes. Surfactants are used to control the interaction between nonhomogeneous components of the reacting system. The properties of the polymer structures may be modified by the use of chain extenders or by cross-linkers. Fire retardants, fillers and pigments may also be added. Blowing agents can be added to the reacting systems to cause foaming. Blowing agents may be nonreactive or reactive. Nonreactive blowing agents act by evaporating within the foaming mix.

## C.2 Reactants

The most important reactant with MDI or TDI is the polyol, as indicated above. There are different ways in which the chemicals used to make polyurethanes are supplied and brought together during processing. MDI and TDI are almost invariably supplied without the incorporation of other polyurethane chemicals (Allport 2003). This is because they react with many products, including water which is often found in polyurethane formulations. A polyurethane system may be supplied as two components, which are the diisocyanate and a complete blend of all the other materials. This approach is very simple, but inflexible as regards formulation and hence final product properties. It is appropriate for long production runs of the same polyurethane product. The ultimate in flexibility is the individual supply and metering of each polyurethane component, using a multi-stream mixing head. With this approach, variations in formulation can be used to produce polyurethanes of different specifications without interrupting continuous processes. The formulation can even be changed during the dispensing of a shot of reacting mix into a mold. For example, composite cushioning with two hardness sectors can be produced in one shot (Allport 2003).

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