QUANTIFICATION OF WATER FOOTPRINT

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Abstract

In most midwestern states water availability is rarely an issue, because there are many lakes and rivers from which to extract water. However, there are areas in the world and even in the United States in which water is not readily available. As the world's population grows and developing nations realize higher standards of living, the amount of water needed will rise. One important use of water is in manufacturing. There are three scopes for water use in manufacturing: direct use in the process (scope 1), through the energy used to perform the process (scope 2), and the water used during manufacturing to create the materials that are consumed (scope 3). One of the most common metals used in manufacturing is steel. This study breaks down the production of steel, from iron ore to raw steel, to quantify a total water footprint. Each step considers scopes 1, 2, and 3. The water used to create one kilogram of steel included 12.8 liters of water for scope 1, 0.2790 liters of water for scope 2, and 692.1 liters of water for scope 3. The process that was responsible for the largest portion of water use was the production of coke. Coke processing (scope 3) uses 98% of the total water needed and should receive the greatest attention in efforts to reduce water use in steel production.

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QUANTIFICATION OF WATER FOOTPRINT:

Calculating the Amount of Water Needed to Produce Steel

Edward J. Kluender, Physics and Chemistry

INTRODUCTION

In 2008, the National Academy of Engineering identified providing access to clean water as one of 14 grand challenges for engineering (NAE, 2008). While water covers 70% of the earth, having a sufficient supply of clean water worldwide is a major concern. In 1990, 55 countries failed to meet basic water requirements of 50 liters per person per day (Gleick, 1996). From small farming communities to large cities, producing goods requires clean water. It is not possible to produce edible crops if a farmer is irrigating fields with polluted water. As a community grows, more clean water is needed to grow food to support everyone.

The largest user of water worldwide is agriculture, but a large water consumer that is often overlooked is industry. When water becomes contaminated during industrial use, this necessitates costly wastewater treatment. To conserve water and reduce the costs of acquiring it and treating it after use, a water footprint must be defined. Only after knowledge is gained about how much water is being used and where it is consumed can technological advances be made to reduce the impact and can efforts be undertaken to attack processes where water is not being used efficiently.

The objective of this study was to calculate a complete water footprint for low-carbon steel. Steel was selected because it is a common metal used in many industrial processes and is made worldwide. Much of the data

used for this calculation was taken from the Ecoinvent Database (Swiss Centre for Life Cycle Inventories, 2007). This study calculated and analyzed how much water is used during each process, from raw material to steel.

METHODS

Water Footprint

A water footprint is the amount of water used to produce a product. Cradle-to-grave analysis is used to break down the total production, from raw materials to final product, into individual processes. To complete a full water footprint, it is necessary to include direct and indirect water usage. Direct use is water that physically is used during a process, while indirect use is water needed to create something used in the process.

Figure 1. Generalized water footprint diagram. Scope 1 is direct, scope 2 is indirect through the energy usage, and scope 3 is tied to the inputs of the process.

As depicted in Figure 1, a water footprint includes three scopes (Ogaldez, Barker, Zhao, & Sutherland, 2012): water used in the process directly (scope 1), water employed to produce the energy used (scope 2), and the water used to produce process inputs (scope 3). Direct water usage is the most straightforward use of water (scope 1). This includes any water used during the process such as the water that is incorporated into the final product and the water used to cool or lubricate. Indirect water consumption is more challenging to visualize and is accounted for in scopes 2 and 3. Almost 90% of the total U.S. energy is thermoelectric, which uses the difference in temperature to create electrical energy. A hot part is heated by the fuel used in the power plant, while the cold part is often cooled with water. Scope 2 takes this water, and other water used in generating electricity, into account. Because the energy breakdown for each country in the world and areas within a country can be different, this aspect of the footprint is location-sensitive.

The second aspect of the indirect water use footprint, scope 3, is the amount of water used to create the inputs for the process. This scope often becomes complicated and difficult to manage. To calculate a complete scope 3, it is necessary to fully work up the product's life cycle (cradle-to-grave). For example, while the final product may only have two inputs, the processes to create those two inputs may include multiple steps, each including its own inputs. In this study, each scope 3 is treated as its own water footprint, complete with another set of scopes 1, 2, and 3. To be thorough, this breakdown needs to begin with the collection of the raw materials and end with the final product.

Each of the three scopes can be split into two categories in their own right: use and withdrawal. Water use is the water that is used for the process and is either incorporated into the product or polluted to the point where it cannot be recycled without heavy treatment. Water withdrawal is the nonconsumptive aspect to the water footprint. While withdrawn water is used, it can be returned to its original source. A problem with calculating water withdrawal is that while water is returned to the source, not all of it will make it back. For example, when water is used to cool, some of the water evaporates and no longer can be considered withdrawal.

Steelmaking Processes

For the entire steelmaking process, there are two main raw materials: iron ore and coal. Iron ore is the base raw material used in the steelmaking process. The majority of iron ore is mined by blast mining (U.S. Environmental Protection Agency Office of Solid Waste, 1994).

Transportation of ore is often very minimal, because most modern mining companies perform on-site beneficiation and pelletizing. Beneficiation is the process in which the iron ore is ground into a finer, more concentrated iron source. Common iron ore ranges from 30% to 65% iron. While the ore is being crushed, water is added for two main purposes. First, water keeps dust to a minimum. Second, water makes it easier to remove impurities. Sifting through a ton of solid ore would be a very slow process if the iron had to travel through a solid. Water reduces friction between all of the particles, making the impurity-removal process more efficient. The final product of this process gives a finely crushed sample of iron, called fines, with some impurities, the most common being silicon.

These fines are then placed in a furnace with limestone, or lime, and dolomite to create impure iron in small pellets. The limestone is used to help remove the impurities. In this study, limestone and dolomite were excluded from the calculation of the total water footprint, because the production of limestone and dolomite requires little water, and each is used in small quantities. There is minimal water usage in pelletizing, because a furnace charged (filled) with only solids is used. Pellets that result are less iron by weight (~52–60% iron) than fines (Gallaher & Depro, 2002).

Pellets are transferred to a blast furnace for the reduction stage. In this stage, coke, a derivative of coal, is first introduced. A blast furnace uses hot air pumped into the bottom of the furnace to react with and melt pellets. Coke is added to introduce carbon. To produce coke, raw coal is heated in an oxygen-less environment. This process serves to burn off impurities in the coal, and without oxygen to combust the carbon into CO₂, a highly concentrated carbonaceous substance is produced: coke. The process ends when the coke is quenched with water. This water, used to remove burned impurities, contains multiple substances including ammonia, tar, and naphthalene (World Bank Group, 1998).

The highly pure nature of coke allows carbon to be added to the iron without introducing new impurities. Steel is carbonized iron, and because carbon is not naturally found in iron, coke is used for its addition. Because carbon is not naturally found in iron, coke is used for its addition. During a reduction process, more carbon is added than is needed for steel, impurities are removed from the slag that forms on top of the iron, and pig iron is produced. Steel contains 0.5–1.5% carbon, and pig iron is classified as any iron that is over 4% carbon by weight. Other than the 4% carbon, the pig iron produced is almost completely free of impurities, often less than 1%. To lower

the carbon content, a basic oxygen furnace (BOF) is used. The BOF is similar to a blast furnace in that it uses hot air blown through the metal, but in this case the air is nearly pure oxygen. The oxygen reacts with the carbon in pig iron to create carbon monoxide, CO, and carbon dioxide, CO₂. The steel that is produced is around 99% iron with carbon and a few other impurities making up the remaining 1%.

This is a very tidy walkthrough of the steelmaking process, but the real process is not nearly as linear. This model assumes all products are inputs for only one other process. The following process breakdown is created using Ecoinvent Database inputs for each subproduct of the steelmaking process (Figure 2). Data from

Ecoinvent begin with a raw iron ore of concentration 46% iron. This is partially beneficiated to contain 65% iron ore. From this subproduct, the beneficiation could be continued to iron fines or it could be used in other processes. Sixty-five percent iron ore is an input for the production of iron fines, iron pellets, pig iron, and even partially in the BOF. Coke also is not added as one lump sum, but rather is added throughout the processes. All of these iron subproducts can be traced back to the 46% iron ore. This is important to ensure that the mass flow “tree,” as seen in Figure 2, has definite ending points at true raw materials. A true raw material is anything that is pulled directly from the earth such that its production cannot be broken down further. Breaking the process all the way down to raw materials is necessary to guarantee

Figure 2. A breakdown of the masses used to create one kilogram of steel. Each box is a product, the inputs of which are connected by an arrow. The “tree” shows the complete breakdown to raw iron ore on each branch.

all water used is accounted for. Scope 3 for the entire process consists of the water used to produce the coke used throughout.

Further adjustments for true cradle-to-grave analysis needs to be done because modern steel is commonly made with scrap iron and/or recycled steel. To get a water footprint of a completely new kilogram of steel, all of the inputs must be able to be broken down to raw materials taken from the earth. To make these adjustments, the amount of recycled steel is removed from the products assuming a one-to-one ratio. Scrap iron is replaced with pig iron.

RESULTS

Each subproduct described below has its own scope 1 and 2. Each individual process' scope 3 is the water footprint of the materials used as inputs for the process. The entire process' scope 3 is the water used to create the coke that is utilized.

To produce partially beneficiated iron ore, two steps are necessary (Figure 3). First, ore is mined from the earth. No water is used directly in the mining process; therefore, there is no scope 1. It takes .001424 kwh to mine 1 kg of iron ore (scope 2). The only input for this process is the explosives used, which has a negligible water footprint (scope 3). The second aspect of this process beneficiation usually occurs on the mine's site. Partial beneficiation uses 1.6582 kg of

46% iron ore (raw iron ore) to produce 1 kg of 65% iron ore. It also takes 1.519 L of water (scope 1) and 0.01872 kwh (scope 2) to make 1 kg. Scope 3 for this process is the scope 2 of the mining process to acquire 46% iron ore.

Fines are the result of the completely broken down iron ore after the full beneficiation process (Figure 4). It takes 1.05 kg of 65% iron ore to produce 1 kg of iron fines. Production of iron fines is the first time in which coke is incorporated into the steelmaking process. In the Ecoinvent Database, coke is quantified in MJ (megajoules, a unit of energy). Included is 1.43 MJ of coke to make 1 kg of iron fines. Scopes 1 and 2 for fines are 0.5 L of water/kg and 0.01 kwh/kg, respectively. Scope 3 is the water used to make the 65% iron ore and the coke used in this process. To make 1 kg of iron pellets, it takes 1.05 kg of 65% iron ore (Figure 5). It takes 0.09 L of water and 0.025 kwh to make 1 kg of iron pellets. Scope 3 for iron pellets is the water used to produce the iron ore that is utilized.

The inputs to produce 1 kg of pig iron are 9.724 MJ of coke, 1.05 kg of iron fines, 0.4 kg of iron pellets, and 0.15 kg of 65% iron ore (Figure 6). To make 1 kg of the high-carbon iron, 6 L of water are used (scope 1). The blast furnace is heated with natural gas, which was investigated as an input but ended up being insignificant in a water footprint. The scope 3 for pig iron is the total of all three scopes of all four of its inputs: pellets, fines, ore, and coke.

Figure 3. The two-step process breakdown to produce partially beneficiated iron ore from raw materials.

	Amount of material used	Water used (L)	Electricity used (kWh)	Scope 2 consumptive water use (L)	Scope 2 non-consumptive water use (L)
46% ore	3.115 kg	0	0.004424	0.01168	0.2648
65% ore	1.875 kg	2.848	0.03506	0.09256	2.0986
sinter	1.17 kg	0.585	0.0117	0.3089	0.70029
pellets	0.444 kg	0.04	0.0111	0.0293	0.6644
pig iron	1.11 kg	6.66	0	0	0
steel	1 kg	2.7	0.02194	0.05793	1.313
coke	12.47 MJ	692.1	0.0213	0.0567	1.285
Totals		704.9	0.1057	0.279	6.326

Table 1. Data compiled from Ecoinvent database (Swiss Centre for Life Cycle Inventories, 2007) using the process breakdown seen in Figure 2.

Two processes are required to get from a raw coal to coke (Figure 7). Coal is first mined, which is predominantly done with blast mining. There are two different types of mines in which coal is mined: open mines and underground mines. Open mines are essentially large pits, while underground mines are concealed below the earth. Open mines use less energy than underground mines, but neither use water directly. Open mines use 3.88×10^{-4} kWh/kg of coal, while underground mines use 6.94×10^{-4}

kWh/kg. Once the coal is mined, it is refined into coke. This direct water use causes the cokemaking process to have a high scope 1 of 55.5 L of water/MJ of coke. It takes 0.0478 kg of coal to make 1 MJ of coke along with electricity 0.00169 kWh/MJ (scope 2).

The final step of the steelmaking process is the basic oxygen furnace. To make 1 kg of steel it takes 1.1 kg of pig iron (after adjustment for recycled steel and iron) and

Figure 4. The process breakdown to produce iron fines from partially beneficiated iron ore and coke.

Figure 5. The process breakdown to produce iron pellets from partially beneficiated iron ore.

0.022 kg of 65% iron ore (Figure 8). In the BOF, these are heated with air and small amounts of natural gas. Scopes 1 and 2 are 2.7 L of water/kg of steel and 0.0219 kwh/kg. Scope 3 for the BOF includes all of the water used to make all of the subproducts that were fed into the furnace to produce 1 kg of steel. Using the mass flow tree, the amount of each product needed to be produced to make 1 kg of steel was summed. To make certain that there is no double counting, scope 3 was not considered to be part of the water footprint.

For the full steel manufacturing process, from raw materials to unalloyed steel, eight processes were analyzed, each with respective scopes 1 and 2. When all of the scope values are added to make 1 kg of steel, it

Figure 6. The process breakdown to produce pig iron from partially beneficiated iron ore, iron fines, iron pellets, and coke.

Figure 7. The two-step process breakdown to produce coke from raw materials.

takes 704.9 L of water (Table 1). By weight, 704.9 kg of water is required to produce 1 kg of steel. Scope 2, the energy water footprint, gives a consumptive water use of 0.279 L and a nonconsumptive water withdrawal of 6.327 L. These numbers were calculated using the energy breakdown of the entire United States in 2010. Because steel is made all over the world and different locations within the U.S. differ, scope 2 calculations will vary by location. Ecoinvent does not explicitly include any data for nonconsumptive water use for any processes; all water data is classified as an input (direct).

SUMMARY AND CONCLUSIONS

As the world population grows, water use grows as well. Clean water is a valued commodity. While water conservation has begun, there is still much to do. In order for policies to be made, a comprehensive understanding of water use needs to become commonplace. The modern world would not have come to be had it not been for the invention of steel. Steel is used across the world in almost every industrial setting in one way or another. With steel being a multiprocess production, many steps needed to be broken down.

The largest water consumer in the steel manufacturing process actually does not involve iron. It is the coke manufacturing process, scope 3 of steel manufacturing. This is because water is used to quench the coke after

Figure 8. The process breakdown to produce steel from partially beneficiated iron ore and pig iron.

it has been cooked. After water is used to quench the coke, it is highly toxic. Water also is used heavily in the beneficiation process for the removal of impurities of the ore. The difference between these two, both using water for the same purpose, is how efficiently water can be reused after the process. In the beneficiation process, nearly 90% of the water used is recirculated and is therefore not consumptive. In coke production, the quenching water is mixed with chemicals and needs to be treated before reuse. The beneficiation process has the highest energy usage. This is not surprising considering it is the only process that uses electrical energy, the rest predominantly relying on natural gas or other fuels for heat.

There are two alterations to the carbonation process that could reduce the water footprint. First is to dry quench coke after it is cooked. This process uses nitrogen gas instead of water to cool and remove the impurities (World Bank Group, 1999). While this would reduce water use, it is less effective cooling. It is important to remember that, for this and other alternatives, lowering water usage may raise other environmental issues or be fiscally inefficient. The other option is to cut out coke entirely as is done regularly by recycling old steel. This does not change the water footprint of a brand new kilogram of steel, but it removes the need for producing completely new material because steel is 100% recyclable.

Future studies in this area could identify the water withdrawal of these processes. The only water in this report, other than from energy, is water use, not withdrawal. To estimate water withdrawal, data need to be collected on the water used to cool steel and its subproducts as they come out of the furnaces. Cooling

will be the biggest source of water withdrawal and will contribute some to the water usage because of evaporation. Further studies could also consider steel that was recycled. An alternative to the basic oxygen furnace is the electric arc furnace (EAF). The EAF method uses a high percentage of recycled steel. With increased recycling, EAF has become a large source of “new” steel that is made. In present-day steel production, it is rare for a new piece of steel to be produced completely from raw iron with no scrap metals used.

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