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Life Cycle Assessment of Abbey Forged Products, With Focus Given to the Placement of the System Boundary

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Abstract

The steel industry is a major contributor to global CO_2 emissions and as a result the industry has implemented global life cycle assessment (LCA) methodology to evaluate the environmental impacts associated with global steel production. In this project these impacts associated with steel production at a Sheffield company, Abbey Forged Products were investigated. Using LCA methodology and online software, SCEnAT, the standard production process was modelled. It was found that the major contributors to the total CO_2 emissions were the unprocessed steel input, the steel extraction process, the factory gas and electricity used. Five different improvement scenarios were suggested and modelled. These scenarios presented problems with where to draw the system boundary of the LCA with each being tackled in different way. The most effective scenarios were found to be using recycled steel and implementing carbon capture technologies.

1 Introduction

The steel industry produces vast quantities of CO_2 due to its energy intensive production. As a result, the World Steel Association (WSA) uses life cycle assessment (LCA) methodology to evaluate the environmental impacts associated with global steel production. A LCA assesses the impacts associated with a process, product or service. A LCA is ran from cradle to grave, starting with raw material extraction and ending with either disposal, recycling or recovery, allowing for all stages of the lifecycle of the subject to be considered (Peaslee, 2008). The results of a LCA are quantifiable and can be compared to similar studies. Consequently, a LCA can be used alongside economic and other assessments to review the overall worth of a subject.

A key step in any LCA is the placement of the system boundary. A standard LCA uses a boundary set from cradle to grave. Primary data is often not available for the upstream and downstream processes in a cradle to grave boundary, requiring the use of secondary data which is less accurate and reduces the quality of the LCA.

Abbey Forged Products (AFP) is a forgemaster based in Sheffield. The aim of this project is to build a basic model for its production using SCEnAT software. This will allow a series of interventions to be modelled and compared in terms of CO_2 emissions and how the system boundary must be modified in order to keep the cradle to grave requirements.

2 Literature Review

2.1 LCA Introduction

The environmental rating of a company or business is measured by monitoring the influence it exerts over the local surroundings (Chubbs and Steiner, 1998). Using a LCA this influence can quantifiably be broken into individual products or services (Klopffer, 1997). There are many proponents of LCAs including the Environmental Protection Agency (EPA). They state “a LCA can allow decision makers to select processes that quantify environmental releases and make the decisions to best impact the environment” (EPA, 2006).

A LCA can help to make a comparison between subjects and can be used alongside other forms of analysis to make comparisons on more than a purely environmental perspective (Peaslee, 2008). A major benefit of LCAs is that they evaluate their subject from cradle to grave (Hendrickson et al., 2010) (Monahan and Powell, 2011). Another benefit is their consideration of both direct and indirect emissions. Direct emissions are caused by the company involved whereas indirect emissions are due to an external source (Hunt et al., 1992).

2.2 LCA History

LCA methodology has existed since 1969, the first cases were developed in both the USA and Europe with an initial aim of assessing the environmental impacts of a product (Hunt et al., 1992) (Klopffer, 1997). An early success of the LCA methodology was a study ran by Coco-Cola. This study investigated the environmental impacts of a range of different drinks containers. The results of this study helped to ‘comfort’ the company with the idea of using plastic containers (Hunt and Franklin, 1996). LCAs experienced a surge in popularity from 1970-80. This coincided with a major oil and consequently energy crisis causing public interest in the energy burdens of a subject (Hunt and Franklin, 1996).

The most famous LCA success is an assessment into a variety of nappies by Franklin Associates. This study found that, over their entire life cycle, disposable nappies have fewer environmental impacts than reusable options. This is because that whilst they generate four times as much waste, their production uses half as much energy and they only generate half as much air pollution (Duda and Shaw, 1997). Similar studies with the same results have been done for paper bags and cups (Hendrickson et al., 2010). In all cases a LCA allows for a compromise to be made between different sources of emissions.

2.3 LCA Operation

There is a standard operating procedure for LCAs which is split into four phases. They are shown in Table 1 (Monahan and Powell, 2011) (Burchart-Korol, 2013).

Table 1 – Phases of the operating procedure of a LCA.

Phase	Description
1	Goal, scope and definition
2	Inventory analysis
3	Impact assessment
4	Interpretation

The goal, scope and definition phase outlines the parameters and boundaries necessary to run a LCA. This includes defining a functional unit that the assessment will be based on (commonly 1 kg or 1 m etc.) and the system boundary, setting the boundary for what is included in the LCA. In this phase the level of detail of the LCA will be decided and categories for the environmental impacts are drawn (Monahan and Powell, 2011) (Pehnt, 2006). Any assumptions that were made should be included (Klopffer, 1997).

The inventory analysis or life cycle inventory (LCI) assesses the requirements of the LCA in terms of energy and raw materials whilst considering any emissions produced (Duda and Shaw, 1997). It is the most developed phase of a LCA relating the requirements from phase one to the production of one functional unit. It categorises data into two groups, specific (obtained on site) and generic (obtained from literature) (Klopffer, 1997). Whenever possible specific data should be used.

The life cycle impact assessment (LCIA) is necessary as a LCI does not make consideration for a subjects' environmental impacts. The LCIA processes the presented data into categories, quantifies the category and then weights it based on its importance. This importance is due to the associated availabilities and environmental burdens (Klopffer, 1997) (Duda and Shaw, 1997).

The interpretation phase reviews the LCA using a mathematical tool with respect to the LCIA. This reviews the quality of the assessment, allowing for the results to be used in comparison to other subjects (Klopffer, 1997). The interpretation identifies any significant issues and makes an evaluation considering completeness, sensitivity and consistency, which allows for conclusions to be drawn. The results of the LCA must be presented in a manner that someone with no knowledge of the assessment can use and understand them (ISO, 2006b).

LCA methodologies can be run using hybrid models. They work by combining the detail of a process analysis method with the large system boundary of an input-output analysis. They are advantageous as they counter the problems associated with the use of generic data and unnecessary paths in a supply chain (Acquaye et al., 2011).

2.4 LCA Drawbacks

Whilst there are numerous examples of the successes of and praise for LCAs, including the work done by Coca-Cola and the praise from the EPA, they suffer from disadvantages that may oppose wide scale application (Hunt and Franklin, 1996) (Duda and Shaw, 1997). Large inaccuracies occur in a LCA applied over an entire industry. This stems from a large number of sources providing data that must be averaged (Duda and Shaw, 1997). This problem is compounded if these different sources obtain this data via different methods or rely on generic data. A solution to this problem is to use databases such as ecoinvent. Ecoinvent can be used as it employs a team to ensure that its data is accurate and up to date (Ecoinvent, 2007).

As technology is changing so rapidly, the results of a LCA can be outdated shortly after its being published. In some examples a LCA may have to rely on obsolete or static data. It can be hard to adapt the system boundaries of a subject to respond to a change in the system, highlighting the need for hybrid LCAs (Acquaye et al., 2011). A process that produces more than one product presents difficulties when determining which emissions are associated with the which product (Duda and Shaw, 1997).

2.5 Steel Production Techniques

Steel production is generally grouped into primary and secondary production (Kim and Worrell, 2002). Primary production uses iron ore as an input whereas secondary production uses scrap. Primary production generally occurs in either a basic oxygen furnace (BOF) or an open hearth furnace (OHF). Compared to BOF, OHF production has lower capital costs but also produces smaller yields. Secondary production generally occurs in an electric arc furnace (EAF) or via direct reduction iron (DRI). DRI uses iron instead of scrap steel but is rarely used as it is energy intensive and has high associated CO_2 emissions. Compared to primary production, secondary production does not have an iron ore input and consequently avoids the energy demands of primary ore production.

Steel production is followed by forging, which occurs by a variety of techniques. Forging may occur inside a cast which is repeatedly rammed (enclosed die forging). This occurs until the steel fills the shape of the cast (Yoshimura and Tanaka, 2000). A similar process can be employed that does not use the cast (open die forging) (Choi et al., 2006). Forging can occur using opposite rollers (roll forging) (Sluzalec, 1984). Roll forging produces a desirable shape of steel using a minimal input.

3 Case Study: World Steel Association LCA

3.1 Framework

The WSA has performed three LCAs of global steel production (Worldsteel, 2010, Worldsteel, 2011). The latest LCA was completed in 2011 and compared 15 different steel products that represent the majority of major steel production, excluding stainless options. This LCA was a global undertaking using data from 49 sites in 17 countries that produce roughly 10% of the total global steel.

The LCA used frameworks and guidelines set by the International Organisation for Standardisation (ISO), in particular ISO 14040 and 14044. It has a functional unit of 1 kg of steel product at the factory gate. It uses a system boundary of cradle to gate not cradle to grave, ending with finished products ready to ship. The end of life stages were ignored as steel is used in so many different processes that the WSA decided it would be too hard to accurately model downstream use.

3.2 Data Collection

The WSA avoided the problems associated with obtaining consistent data across an industry. It achieved this by distributing an identical spreadsheet to each site involved in the study. This spreadsheet was completed in an identical manner every time data was collected for the study over a period of one year of production.

The indirect emissions associated with steel production were included in this assessment on a case by case basis. Internal transport was excluded as the accompanying environmental impacts were decided to be negligible. External transport was included; data was obtained by noting the duration of each journey alongside the form of transport used. Coal and electricity were both included, as their related environmental impacts would vary globally the impacts from local production and generation were counted. This would include any transport or infrastructure needed to connect the utilities to the sites.

3.3 Further Work

As this LCA set the system boundary at cradle to gate, it did not factor in end of life effects. It included suggestions for including these effects (Equation 1).

$$\text{LCI for 1 kg of steel product including recycling} = \text{X - (RR - S) Y}(\text{X}_{pr} - \text{X}_{re})$$

Equation 1 – Closed loop recycling life cycle equation.

Equation 1 shows the LCI impacts associated with recycling 1 kg of steel product. The existing cradle to gate LCI is represented by X. RR – S is the net scrap produced by the system. RR is the recycling rate and S is the scrap input. $Y(X_{pr} - X_{re})$ is LCI value of the scrap steel. Y is the process yield of the steelmaking, X_{pr} is the LCI for 100% primary metal product and X_{re} is the same for secondary metals.

This LCA included numerous manufacturing processes with more than one product, necessitating the use of a co-product allocation system, which would allow the associated inputs and outputs of individual products to be related. The system expansion method used accredits individual inputs and outputs to the major process whilst noting their contributions to process gas and slag production.

3.4 Results

This LCA evaluated the data via five different methods. They are shown in Table 2.

Table 2 – LCA methodology used.

Method		Units
Primary energy demand	PED	MJs
Global warming potential	GWP	kg of CO_2 equivalent
Acidification potential	AP	kg of SO_2 equivalent
Eutrophication potential	EP	kg of phosphate equivalent
Photochemical oxidant creation potential	POCP	kg of ethane equivalent

The methods most comparable to the AFP study are PED and GWP. Table 3 shows the results of the WSA study in terms of PED and GWP.

Table 3 – LCA results for steel products.

Steel production technique	LCA methodology	PED (MJ)	GWP (kg CO_2 e)
Sections,	Cradle-to-gate	19.6	1.6
1 kg	Including recycling	16.4	1.2
	Recycling benefit	-3.2	-0.4
Hot-rolled coil,	Cradle-to-gate	21.6	2.0
1 kg	Including recycling	11.9	0.9
	Recycling benefit	-9.7	-1.1
Hot-dip	Cradle-to-gate	27.5	2.5
galvanised steel,	Including recycling	17.5	1.3
1 kg	Recycling benefit	-10.0	-1.2

The GWP results are shown in Figure 1 and Figure 2.

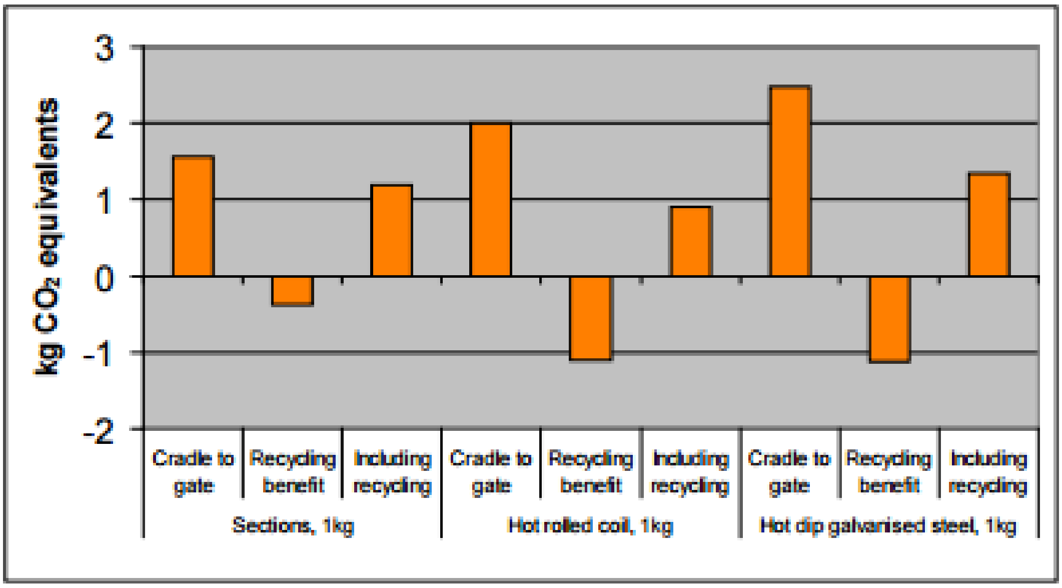

Figure 1 – GWP of steel products.

Figure 1 shows that when the system boundary is set to be cradle to gate, steel production via sections performs most ideally. When recycling is included, hot rolled coil is the most ideal production method. Sections production occurs using a hot rolling mill.

Figure 2 shows individual contributions to the GWP of the different production techniques. Over 90% of the CO_2 produced is a result of existing CO_2 in the system.

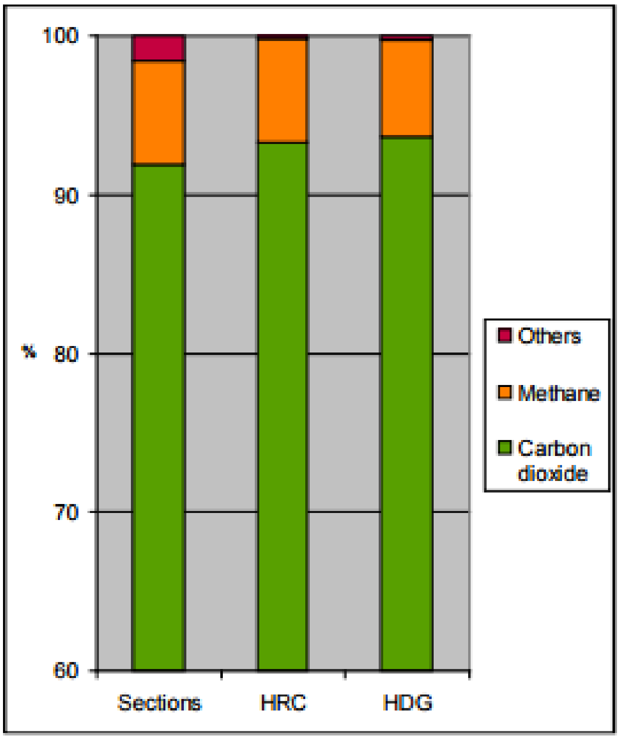

Figure 2 – Contributions to GWP of different steel products.

4 Methodology

4.1 LCA Framework

The LCA for AFP followed the protocols set by the ISO, in particular ISO 14040 and 14043 (ISO, 2006a, ISO, 2006b). It uses the usual four phases which were explained in section 2.3.

4.2 Goal of the Study

The LCA aims to carry out a cradle to grave study for standard production at AFP. It uses primary data provided by the company and secondary data sourced from literature. Using this data a model for the standard production will be constructed; five interventions to reduce the CO_2 emissions will be planned, modelled and compared.

4.3 System Boundaries and Functional Unit

The system boundary is cradle to grave. It includes processes such as transport, extraction, the provision of utilities and the end of life disposal. It excludes processes such as the manufacturing of the necessary infrastructure (i.e. the roads and buildings), the daily activities of the staff and any additional work carried out by the consumers.

The functional unit of this study is 1 kg of steel products.

4.4 Data Sources

Primary data provided by the company was used when possible. This data was presented in variety of forms from utility bills and drivers log books to production records. The secondary data was sourced from literature and databases. Whenever secondary data was utilised it was assumed that the data is relevant to the production process used by AFP, any inaccuracies created by the use of secondary data were assumed to be negligible.

The model was manufactured using SCEnAT online software. SCEnAT is a tool allowing the LCA methodology to be carried out, using a hybrid LCA model.

5 Results and Discussion

5.1 Basic Model

The first step in this assessment was to model the basic production process at AFP. This model uses both primary and secondary data and is shown in Figure 3. The transport, materials and utilities processes all utilise exclusively primary data. The heat treatment and disposal processes use secondary data sourced from ecoinvent (Ecoinvent, 2007). The steel extraction process uses secondary data from a mining journal (Farrell, 2009).

The SCEnAT software provides data for missing inputs (indirect emissions). The indirect emissions included are shown in Table 4. These emissions are cause by an external source, not AFP. These sources can be external companies (waste contractors) or external activities of the staff (commuting).

Table 4 – Missing inputs from the SCEnAT software.

Missing input	Domestic or international
Waste incineration	Domestic
Waste collection	Domestic
Waste landfill	Domestic
Other chemical products	Domestic
Inorganic basic chemicals	Domestic
Passenger land transport	Domestic
Passenger air transport	Domestic
Passenger rail transport	Domestic
Building construction	Domestic
Oil extraction	International
Gas extraction	International
Telecommunications	Both

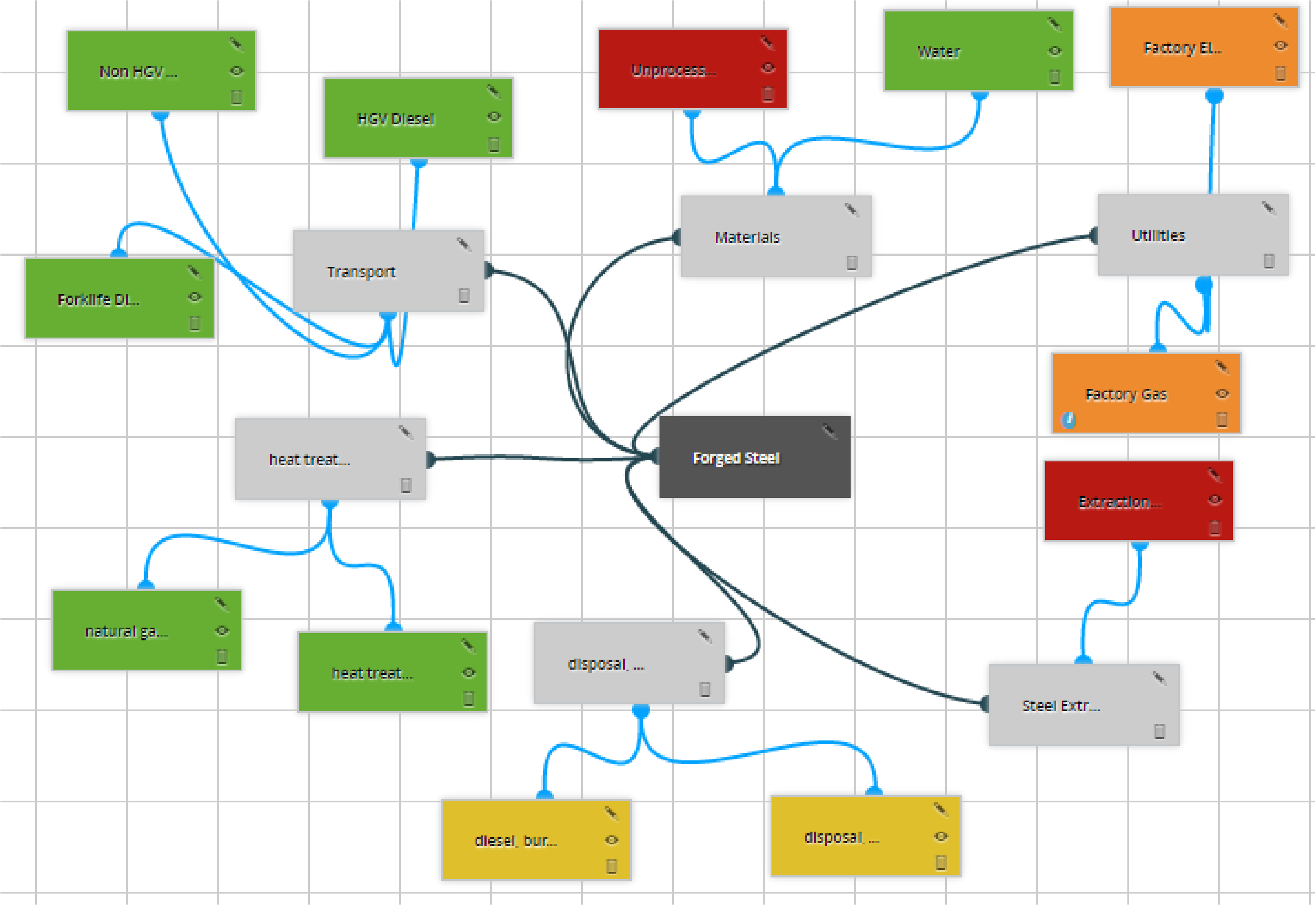

Figure 3 – SCEnAT model for standard production.

The results are that the system produces 4.4771 kg CO_2e/kg of steel product. The annual steel production at AFP is 3,852,000 kg of steel products. From this, the annual CO_2 emissions from AFP are 17,246,000 kg. The major sources of these CO_2 emissions are shown in Figure 4; they are unprocessed steel (42.2%), steel extraction (38%), electricity (9.8%) and gas (5.9%).

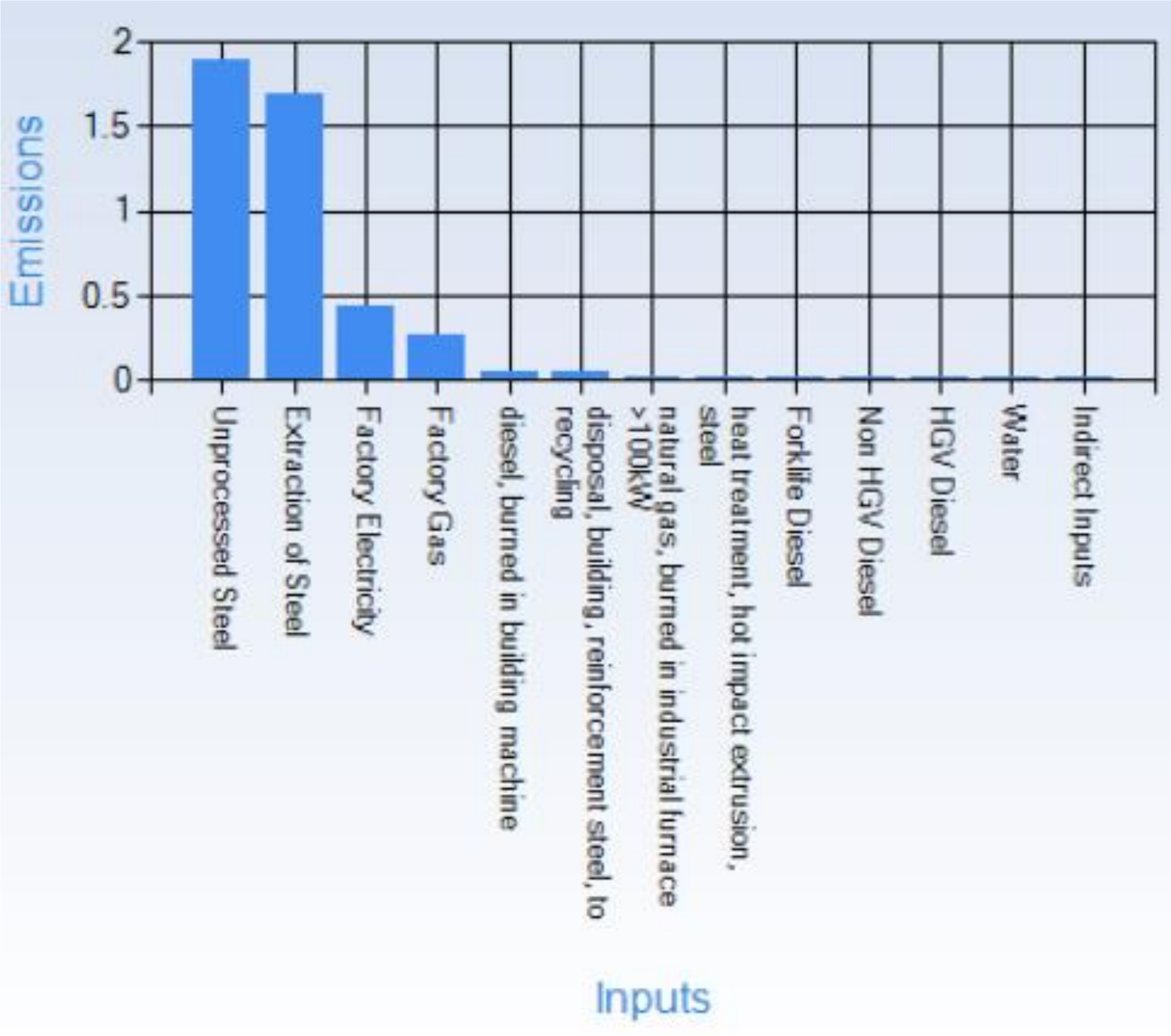

Figure 4 – Emissions breakdown in the model for standard production.

5.2 Intervention 1

The first intervention changes the source of the electricity used. In the basic model the factory electricity accounts for 9.8% of the total emissions. This intervention suggests sourcing the electricity from wind turbines instead. This would reduce the greenhouse gas (GHG) intensity of the factory electricity from 0.5846 to 0.026 kg CO_2e/kWh (WNA, 2011). In order to satisfy the cradle to grave system boundary the model has been expanded to include the production of the wind turbine. The was done using secondary data from ecoinvent (Ecoinvent, 2007) and is shown in Figure 5.

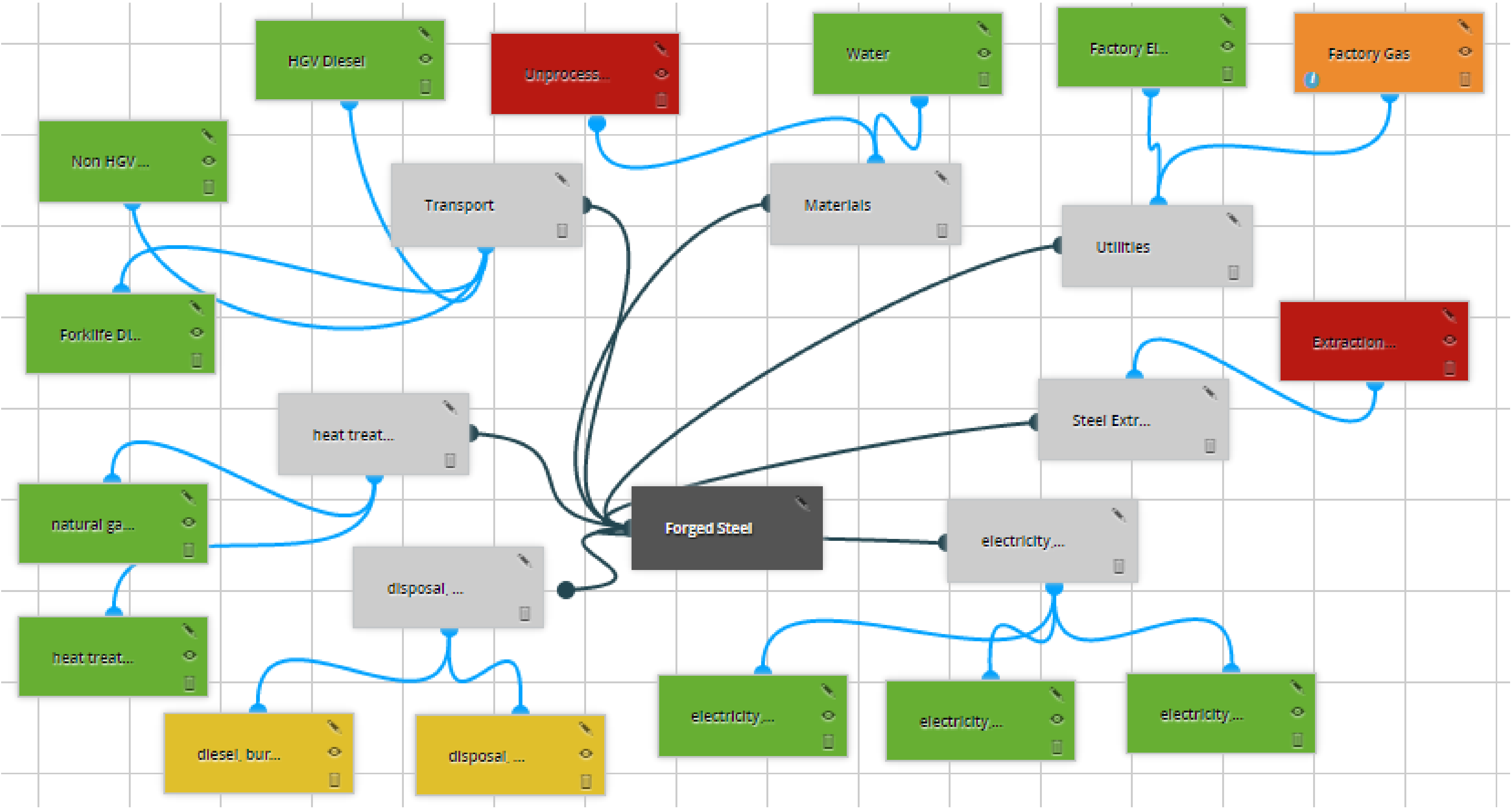

Figure 5 – SCEnAT model for intervention 1 showing the addition of the electricity generation stream.

Intervention 1 reduced the CO_2 emissions of the production process from 4.4771 to 4.0830 kg CO_2e/kg of steel product. This is a saving of 0.3941 kg CO_2e/kg of steel product or an annual saving of 1,518,100 kg of CO_2. The emissions associated with the production of electricity have reduced from 0.4391 (9.8%) to 0.0195 (0.5%) kg CO_2e/kg of steel product.

The major sources of CO_2 emissions have changed and are shown in Figure 6; they are now the unprocessed steel (46.3%), steel extraction (41.6%) and gas (6.5%).

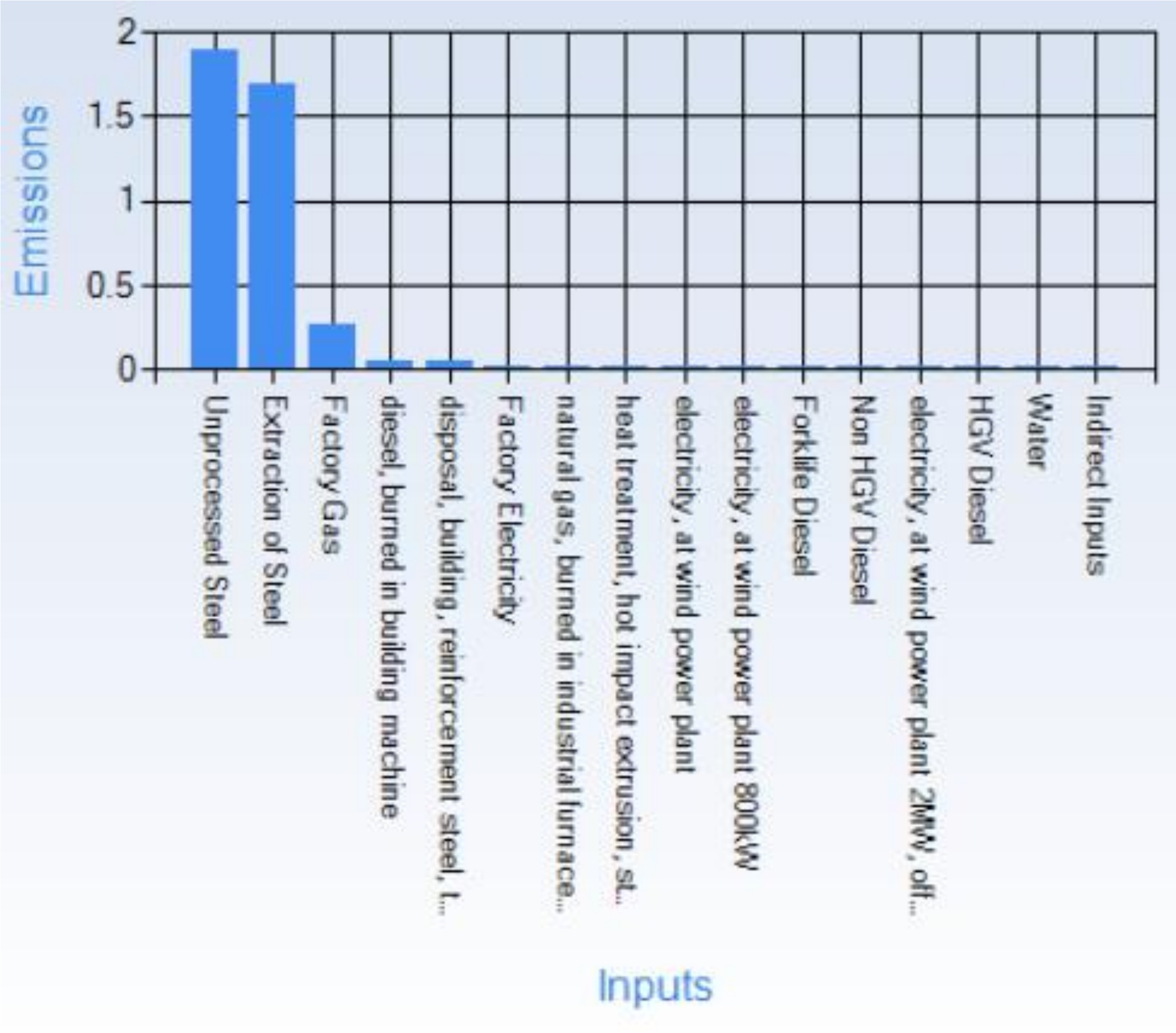

Figure 6 – Emissions breakdown in intervention 1.

5.3 Intervention 2

The major contributions to the total CO_2 emissions in the basic model are due to the unprocessed steel. Intervention 2 uses recycled scrap steel instead, reducing the GHG intensity of the steel from 1.7555 to 0.884 kg CO_2e/kg (Hill et al., 2012) and allows for the steel extraction to be removed from the model. Intervention 2 does not easily fit the cradle to grave system boundary; it is unclear if the CO_2 emissions associated with the recycling of the steel input belongs to this process or their original production. It was decided to include them in this process, increasing the weight of the steel recycling steam. The model used for intervention 2 is shown in Figure 7.

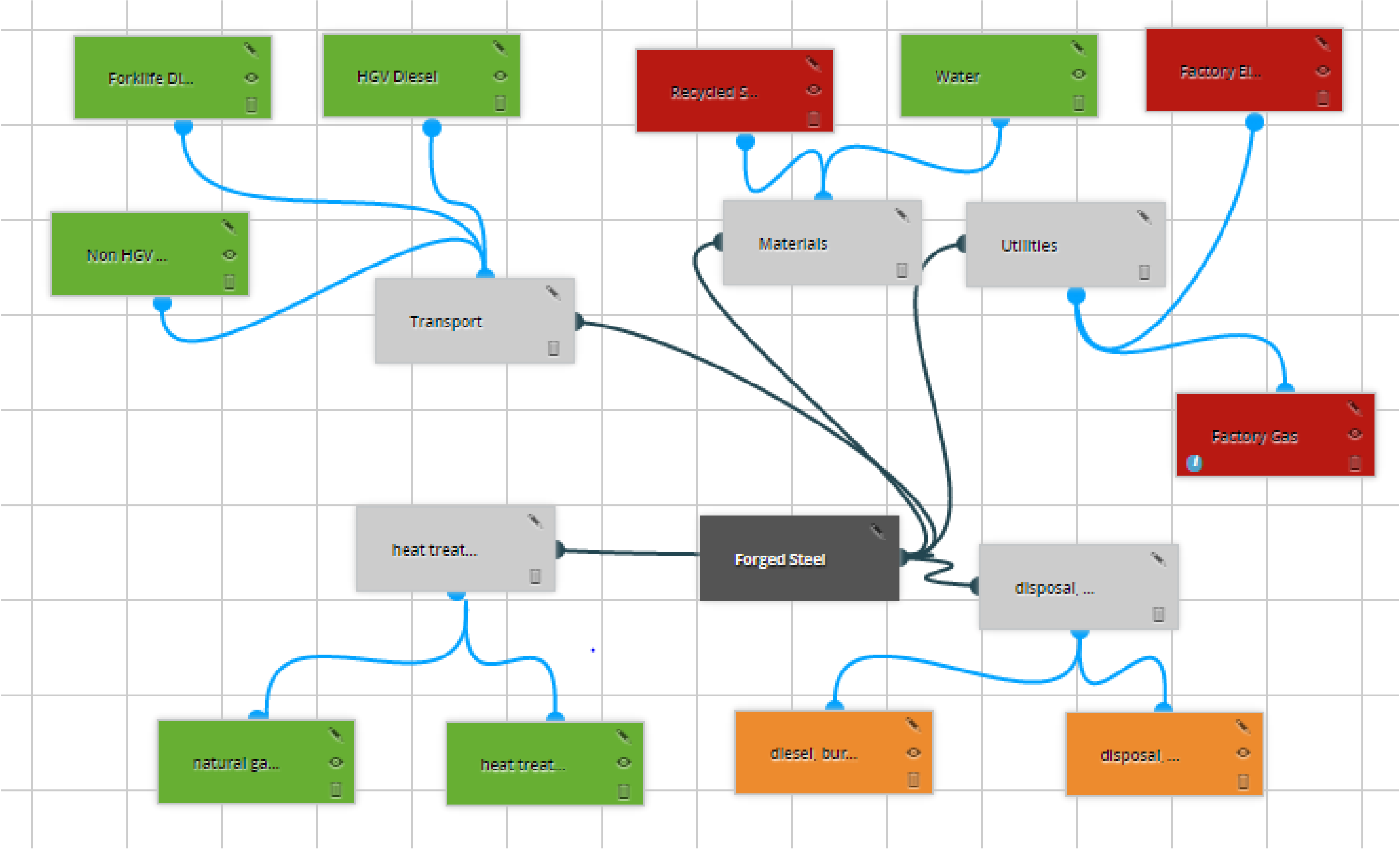

Figure 7 - SCEnAT model for intervention 2 showing the removal of the recycling stream.

Intervention 2 reduced the CO_2 emissions of the production process from 4.4771 to 1.9269 kg CO_2e/kg of steel product. This is a reduction of 2.5502 kg CO_2e/kg or an annual reduction of 9,823,400 kg CO_2e. The emissions associated with the steel extraction have been removed and the emissions associated with the steel have reduced from 1.89 (42.2%) to 0.9517 (48.5%) kg CO_2e/kg of steel product.

The major sources of CO_2 have changed again, they are shown in Figure 8. The steel is still the major contributor with 48.5%, the other major contributors are still the electricity (22.4%) and gas (13.5%). The processes associated with the steel recycling, the diesel used and the disposal itself, are now significant contributors to the total emissions, with 6.1% each.

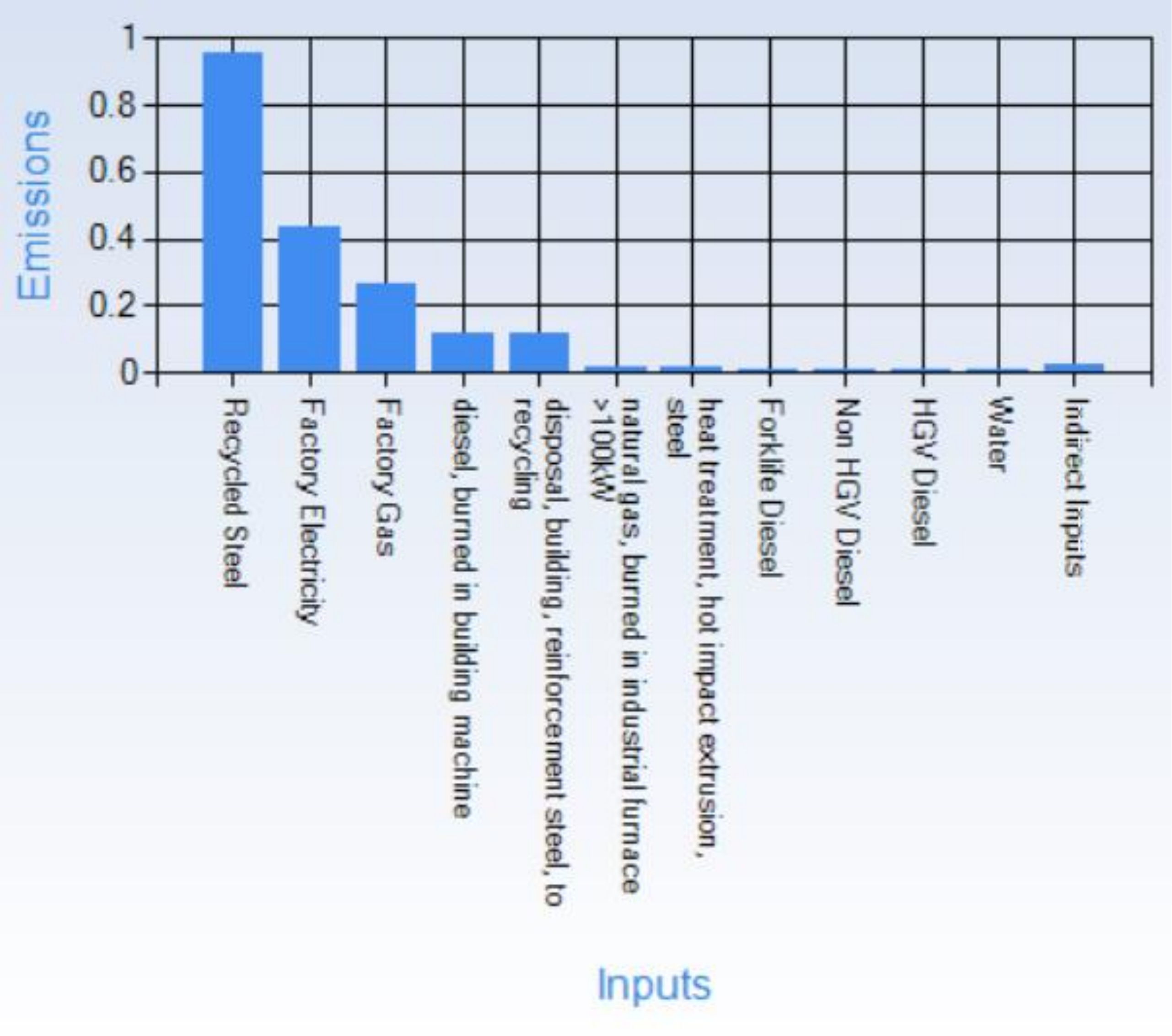

Figure 8 – Emissions breakdown in intervention 2.

5.4 Intervention 3

Intervention 3 utilises the waste heat from the forging process (Figure 9). It suggests a heat recovery system reducing the electricity needs. A report from Newcastle University states that heat recovery at the end of the sinter strand would save 0.734 MW of power (University., 2011). This is a saving of 1,761,600 kWh per annum, reducing the electricity needs to 0.2808 kWh/kg. In order to fit the system boundary, indirect inputs have been included for the heat recovery system.

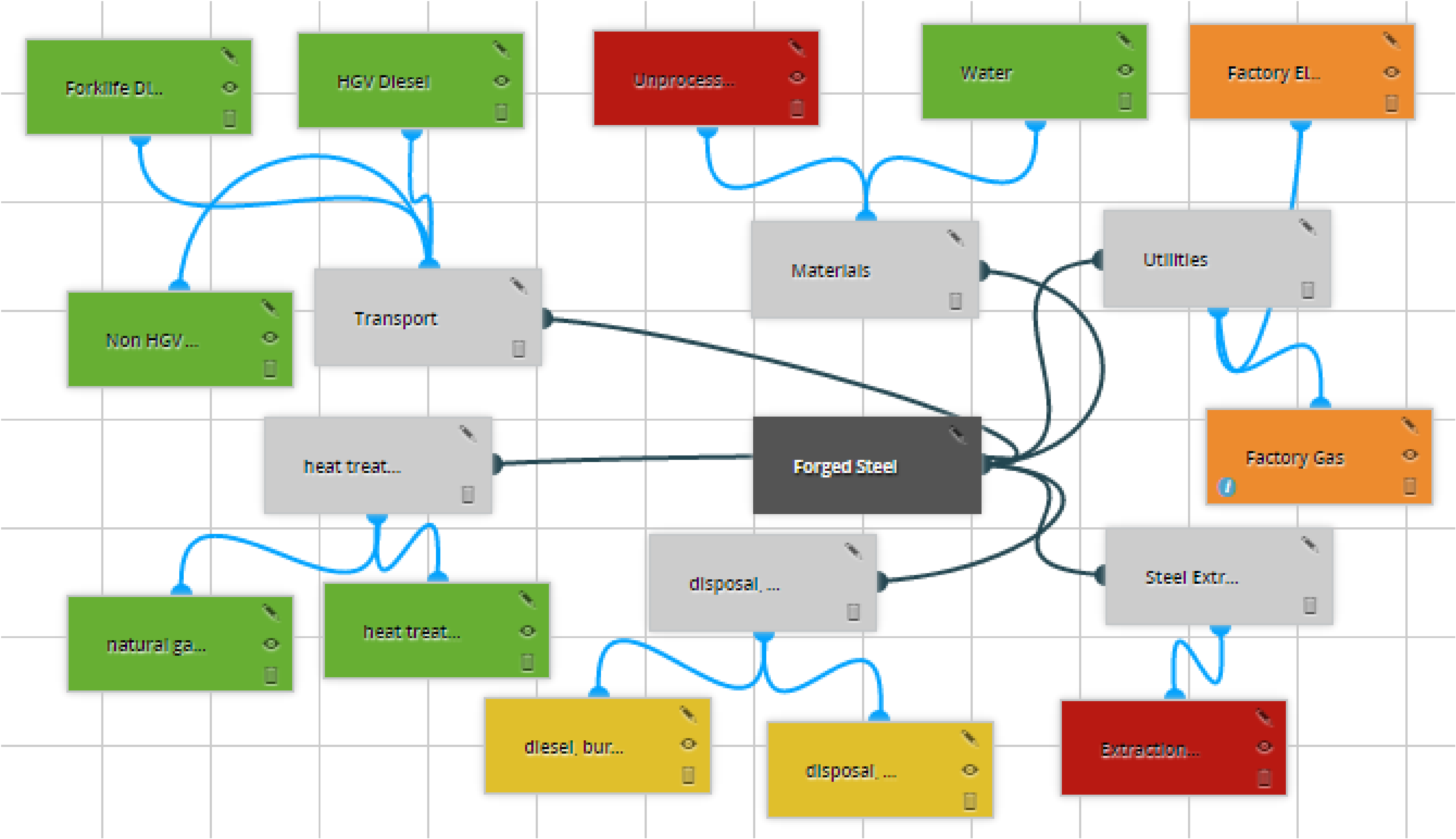

Figure 9 - SCEnAT model for intervention 3.

Intervention 3 reduced the CO_2 emissions of the production process from 4.4771 to 4.2962 kg CO_2e/kg of steel product. This is a reduction of 0.1809 kg CO_2e/kg or an annual reduction of 696,830 kg CO_2e. The emissions associated with electricity have reduced from 0.4391 (9.8%) to 0.2523 (5.9%) kg CO_2e/kg of steel product.

The major contributors to the CO_2 emissions have changed again. They are now the unprocessed steel (44%), steel extraction (39.6%), gas (6.2%) and electricity (5.9%). As electricity is still a major contributor to the total CO_2 emissions further heat recovery could be utilised. The breakdown of the CO_2 emissions is shown in Figure 10.

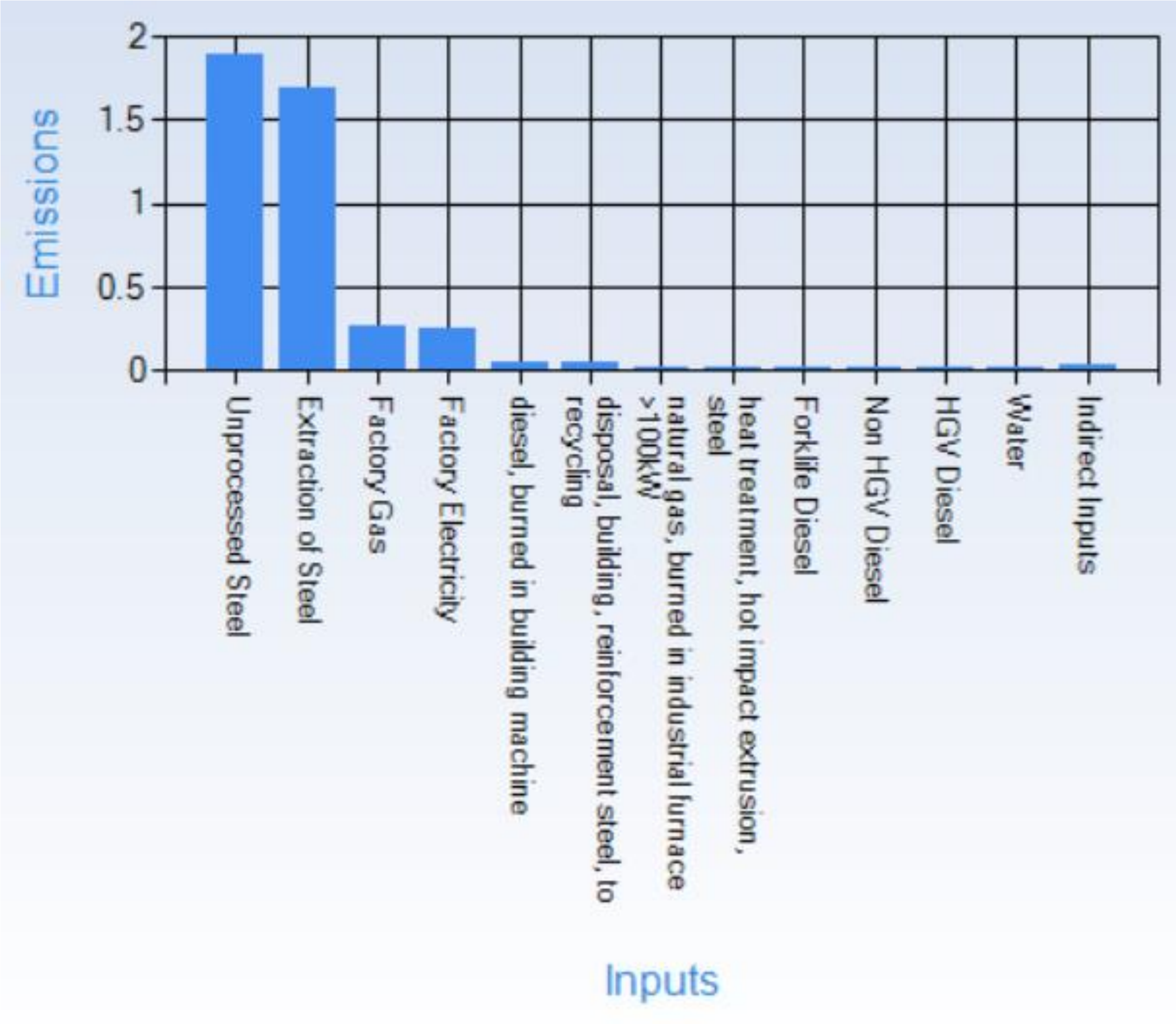

Figure 10 – Emissions breakdown for intervention 3.

5.5 Intervention 4

Intervention 4 utilises best available technologies (BATs) to reduce the CO_2 emissions from the production process. A report published in an energy journal lists a large number of BATs (Worrell et al., 2001). If the five most effective technologies are implemented then there will be CO_2 savings of 0.26195 kg CO_2e/kg. These five technologies are shown in Table 5.

Table 5 – Best available technologies considered.

Number	Technology
1	Injection of natural gas to 140 kg/thm
2	BOF gas and sensible heat recovery
3	Adopting continuous casting
4	Thin slab casting
5	Cogeneration

This would reduce the overall CO_2 emissions to 4.2152 kg CO_2e/kg of steel product or an annual saving of 1,009,000 kg CO_2e.

5.6 Intervention 5

Intervention 5 utilises carbon capture and sequestration (CCS) technology. CCS works by capturing CO_2 at point sources and injecting it into geological formations where it can be sequestered for thousands of years (Figueroa et al., 2008). There are many different techniques that can implement CCS which could reduce the CO_2 emissions from a point source by up to 90% (D'Alessandro et al., 2010). This would reduce emissions from AFP to 0.44771 kg CO_2e/kg of steel product with annual CO_2 emissions of 1,724,600 kg CO_2e. This is an annual saving of 15,521,000 kg CO_2e.

This creates problems with the system boundary. As the LCA is cradle to grave the emissions associated with the CCS process must be included in the final value. As CCS is a new and complicated technology there is no secondary data showing its life cycle effects. Consequently it will not be fully included in this study and should be added when the data becomes available.

6 Conclusion

Every intervention presented a different saving in CO_2. Table 6 shows a comparison between the five interventions and the basic model. It suggests that the most effective interventions are intervention 2 and intervention 5, using recycled steel and CCS. Other factors that affects the suitability of these interventions, such as their costs and efficiencies were not considered in this assessment. It is also worth considering that these interventions do not need to be implemented individually. Also, some of the interventions did not easily fit the cradle to grave system boundary. As a result of the above three notes, the results shown in Table 6 may not be fully accurate.

Table 6 – Comparison of the CO_2 emissions from the different possible interventions.

Intervention	CO_2 emissions per kg (kg CO_2e/kg of steel product)	Annual CO_2 emissions (kg CO_2e)
Base model	4.4771	17,246,000
1	4.0830	15,728,000
2	1.9269	7,422,400
3	4.2962	16,549,000
4	4.2152	16,237,000
5	0.44771	1,724,600

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