Engineering Reduced Greenhouse Gas Production: A Remanufacturing solution.

A life cycle greenhouse gas assessment of remanufactured refrigeration and air conditioning compressors

January 2010

Dr Wahidul Biswas and A/Prof Michele Rosano

Centre of Excellence in Cleaner Production
Curtin University of Technology

This project is carried out under the auspice and with the financial support of Recom Engineering, Osborne Park, Western Australia

ACKNOWLEDGEMENTS

This report is an output of the research project of Recom Engineering in Western Australia on 'Life cycle greenhouse gas assessment of remanufactured compressors'. The research was conducted by Curtin University of Technology through its Centre of Excellence in Cleaner Production in close collaboration with Recom Engineering.

The author acknowledges A/Prof Michele Rosano, Director, Centre of Excellence in Cleaner Production, Curtin University of Technology, for her wholehearted support, guidance and encouragement; Mr Peter Frey, Mr Garry Mahon and Ms Nichole Doerffer from Recom Engineering for providing useful consultation, information and documents to carry out this project, and Mr. John Clegg, Business Advisor, Enterprise Connect, WA for consultation and project development.

CONTACT DETAILS

For queries and comments on this report, please contact:
Dr Wahidul Biswas
Senior Lecturer
Centre of Excellence in Cleaner Production
Curtin University of Technology
GPO Box U 1987, Perth
WA 6845, Australia
Tel. +61 (0)8 9266 4520
Fax +61 (0)8 9266 4811
Email: w.biswas@curtin.edu.au
Internet: http://csrp.com.au

EXECUTIVE SUMMARY

By providing customers with remanufactured products, companies can provide the same level of service using fewer resources. In this way, remanufacturing can importantly reduce the resource intensity and increase the eco-efficiency of product systems (Kerr and Ryan 2000).

By utilising recovered end of life (EOL) parts, remanufacturing should be able to reduce the environmental costs associated with both the manufacturing and disposal of heavy and material intensive industrial machinery. Recom Engineering in Perth, Melbourne, Sydney and Brisbane remanufactures refrigeration and air conditioning compressors using aluminium, copper and steel parts from retired or broken compressors.

A life cycle assessment (LCA) has been carried out to determine the greenhouse gas emissions from the production of a remanufactured compressor versus a new (OEM-original equipment manufacture) compressor. The remanufacturing consisted of five stages: disassembling, cleaning and washing, machining, reassembling, and testing. The analysis determined that remanufactured compressors produce about ***89% to 93% less greenhouse gas emissions*** than ***those associated with a new (OEM) compressor.*** The analysis also confirmed that additional reuse and less replacement of parts with new parts, can further reduce the overall carbon footprint of remanufactured compressors.

This research can assist Recom Engineering in both managing the carbon footprint of its remanufacturing business as it pertains to future carbon trading schemes in Australia and assist in the market development of remanufactured compressors as more sustainable alternatives to the traditional purchase of new OEM compressors.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIXES

1 BACKGROUND

Achieving eco-efficient production and consumption systems requires 'closing the loop' to create cyclic systems in which resources are recovered from the waste stream at the end of life (EOL) of a product. For some manufacturers, the economic efficiency of remanufacturing is clear and it has become a widely held assumption that such systems would also be more eco-efficient (Kerr and Ryan 2000).

By utilising recovered end of life (EOL) parts, remanufacturing should be able to reduce the environmental and economic costs associated with both the manufacturing and disposal of heavy and material intensive industrial machinery (Kerr and Ryan, 2000). Nationally, Recom Engineering remanufactures refrigeration and air conditioning compressors using aluminium, copper and steel parts from retired or broken compressors. A life cycle assessment (LCA) analysis has been carried out to estimate the environmental benefits (ie lowered GHG production) associated with the potential substitution of a new OEM compressor with a remanufactured compressor.

2 METHODOLOGY

The LCA analysis has been conducted according to the ISO 14040-43 LCA methodology guidelines. The ISO14040-43 guidelines ISO (1997) are divided into four steps: 1) goal and scope definition; 2) inventory analysis; 3) impact assessment; and 4) interpretation (as presented in the 'Results' section of this paper). Figure 1 shows the four methodological steps of a typical LCA.

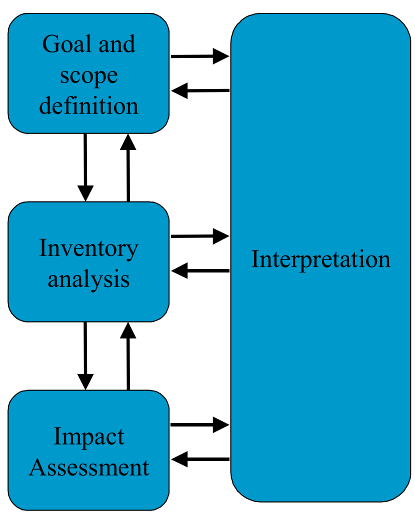


Figure 1. Four step procedure for Life Cycle Assessment (LCA).

2.1 Goal and scope

The goal is to determine the carbon footprint (i.e. greenhouse gas emissions) associated with both a new and remanufactured 20 HP (or 15 kW) compressor for the refrigeration or air conditioning industry. The scope of this research is limited to a '*cradle to gate*' assessment. This means that the LCA does not take into account the compressor utilisation and disposal stages. The LCA, therefore, only assessed the global warming impacts directly attributed to the production of both a new and remanufactured compressor.

2.2 Life cycle inventory (LCI)

Undertaking an LCI is an important initial step in order to carry out an LCA analysis. A Life cycle inventory (LCI) database was built that includeed all inputs involved in the production of both a new and remanufactured compressor.

<u>LCI of a new (OEM) compressor:</u> The life cycle inventory of a new (OEM) compressor was broadly divided into three stages (see Figure 2).

Stage 1: Encompasses the initial mining of raw materials and the manufacturing of metal product/components (i.e. aluminium, cast iron, copper, steel).

Stage 2: Includes the conversion of metal to compressor parts and associated foundry,casting and associated machining processes. However, individual parts and their associated foundry operations were not available in the LCA software database to calculate their GHG emissions. As a result, a new database was created from the iterature. As can be seen in Figure 2, the secondary information on energy and material consumption for foundry operations for aluminium, cast iron, copper and steel was also replaced with data from publicly available literature (Sutherland *et al.*, 2008; World Foundry Organization, 2008; US Department of Energy, 2007).

Third stage: Assembling of compressor parts.

The weight and type of materials for different parts of this new compressor were based on the information provided by Recom Engineering, Osborne Park, Western Australia. Since metal is often lost during the foundry operation, 4%, 5%, 3%, and 3% metal loss in foundry operations was used for aluminium, cast iron, copper and steel, respectively (US Department of Energy, 2007). The information on energy consumption for machining purposes (e.g. drilling, grinding, turning by lathe etc.) was obtained from Brian Boswell (*pers. comm.*. Mech. Eng., Curtin University). Finally, the energy consumption associated with the assembling process was obtained from Neri *et al.* (2000).

<u>LCI of a remanufactured compressor:</u> The life cycle of a remanufactured compressor typically involves the disassembly, cleaning and washing of parts, reconstructing or repair of parts, reassembly and testing. The data format sheet was developed to determine the energy and material for each stage of remanufacturing. All available data with regard to remanufacturing was obtained from Recom Engineering, Osborne Park, Western Australia. Table A1 in the Appendix shows the breakdown of energy and material consumption for disassembly, cleaning and washing (C&W), machining, reassembling and testing operations for the remanufactured compressor parts. This table also shows the weight and type of materials for different parts of the disassembled compressor. The total weight of the compressor has been estimated to be 167 kg.

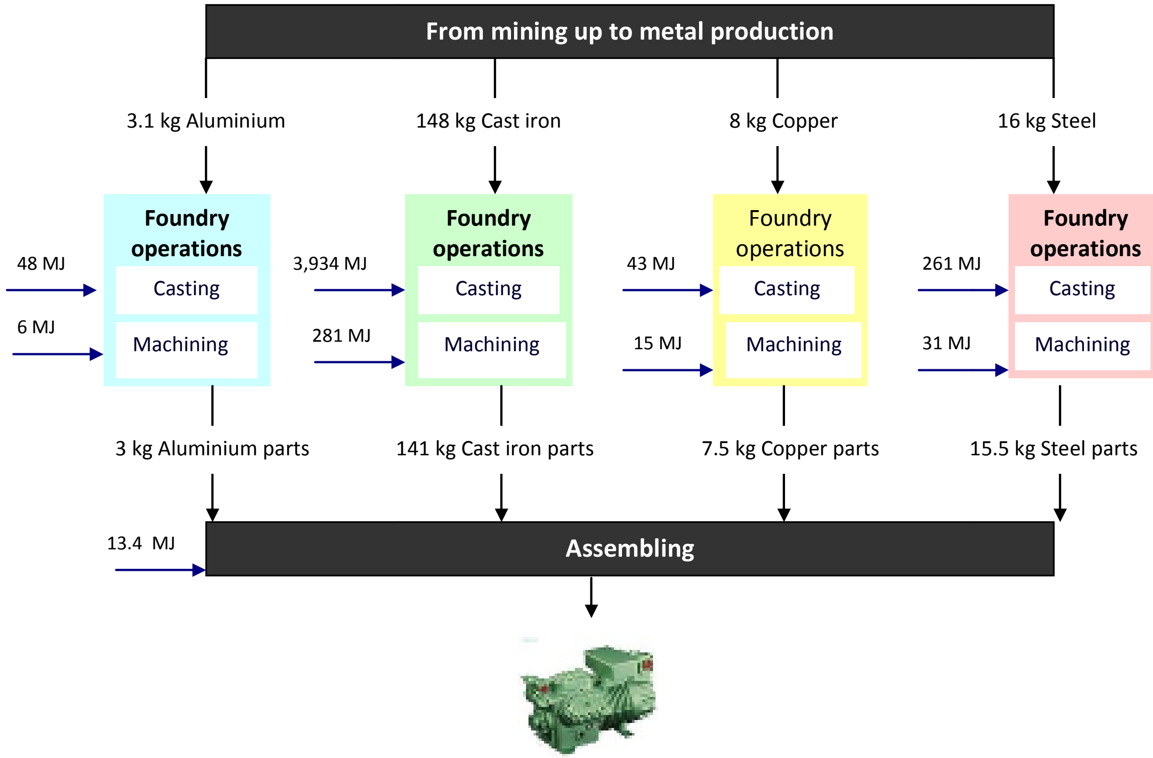


Figure 2. Life cycle inventory of a new compressor (OEM).

2.3 Impact assessment

The greenhouse emissions assessment of producing both a new (OEM) and remanufactured compressor includes two steps. Firstly, the energy and material flow data provided in the LCI were formulated into *Simapro* 7 software (PRé Consultants 2008) to calculate the GHG emissions from the production of both a new (OEM) and remanufactured compressor. Secondly, the program then converted each selected GHG emission into CO_2 equivalents (i.e. kg of CO_2 e-).

Step1: The input and output data in the life cycle inventory were put into the Simapro 7 software to ascertain the greenhouse emissions due to the production of both a new (OEM) and remanufactured compressor. The input and output data from the life cycle inventory were linked to relevant libraries in Simapro 7. The LCA Library is a database, which consists of energy consumption, emission and materials data for the production of one unit of a product. The units of input and output data from the life cycle inventory depend on the units of the relevant materials in Simapro or its libraries (PRé Consultants 2008).

Chemical libraries: Since the cleaning and washing operations are done locally, the libraries from the Australian LCA database (RMIT 2005) for these chemicals was first chosen to calculate greenhouse gas emissions associated with the production of cleaning and washing operation chemical inputs. The database for phosphoric acid was only found to be available in the Simapro database. The emission factors for sodium carbonate (alkali), methyl ethyl ketone (thinner) and Dymethylamine (decarbonizer) were obtained from the Eco-invent database (SCLCI 2007), as local databases were unavailable (RMIT 2005).

The library for the chemical Penetrene was also not found in the Simapro database. Neither emission factors nor energy consumption values for Penetrene were available in the literature. Therefore, emission factors from the Simapro database for the two main ingredients of Penetrene (petroleum distillate and tetrachlorethylene) have been used to determine the equivalent emission factor for Penetrene.

Energy and metal libraries: The aluminium, cast iron, copper and steel libraries of *Simapro* software provided the emission factors for the mining and up to manufacturing of metal products. Since new compressors were initially manufactured in Germany, the German emission factor for electricity generation has been considered to estimate the electricity usage required to make a new (OEM) compressor. In the case of emission factors for the mining of metals and metal production operations, the analysis has utilised relevant European LCA databases.

Since the cleaning and washing, machining, reassembling and disassembling, testing operations are done in WA, a local emission factor for electricity generation has been considered for these processes to estimate the carbon footprint of these operations. In some cases, the components of the compressor cannot be reused and therefore, they need to be replaced with either new parts or fully serviceable pre used parts. If they were replaced with new parts, the emissions from the production of these replaced parts were included. No emissions from the replacement with pre used parts have been included in the analysis.

Transportation libraries: The unit for transport by ship was considered as tonne-kilometre (tkm). For example, 2,008 tkm is required to carry 167 kg of a new (OEM) compressor for 12,026 km (i.e. 0.167 tonne x 12,026 km) from Germany to Perth. The GHG emission factor for tkm for ship was obtained from the simapro software database.

Step 2: Simapro software calculated the greenhouse gas emissions once the inputs and outputs were linked to the relevant libraries. The program sorted greenhouse gas emissions from the selected libraries, and then converted each selected greenhouse gas to CO_2 equivalents (Table 1). The Australian Greenhouse Gas calculation method, developed locally (RMIT 2005), was used to assess the global warming impacts of a new (OEM) and remanufactured compressor.

Table 1: Conversion factor for selected greenhouse gases (RMIT 2005).

GHGs	Conversion factor	Unit
CO_2	1	kg CO_2 eq/kg of CO_2
CH_4	21	kg CO_2 eq/kg of CH_4
N_2O	310	kg CO_2 eq/kg of N_2O

3 ANALYSIS OF RESULTS

3.1 Description of scenarios

The analysis reviewed carbon footprints of remanufactured compressors across three different scenarios. Approximately 99%, 50% and 54% of all parts can be reused through cleaning, washing and machining operations for Remanufacturing Scenarios I, II and III, respectively, which are detailed in Table 2. Table 2 shows the parts of the remanufactured compressor, which underwent different levels of remanufacturing operations, such as C&W, machining and rewinding, replacement with new and pre used parts in Scenarios I, II and III.

These scenarios, which were developed on the basis of Recom Engineering's remanufacturing experience in Osborne Park, WA are summarised below:

Scenario I: 99% of the parts (on the basis of weight) were reused by cleaning, washing and machining operations and less then 1% was replaced with new parts

Scenario II: 50% of the total parts were reused and the rest were replaced by new and pre used parts.

Scenario III: 54% of the total parts were reused and the rest were replaced by new and pre used parts.

The only difference between scenarios II and III is that the oil pump housing was replaced with a pre used oil pump housing in Scenario II, but was reused in Scenario III (see Table 2).

Table 2: Description of Remanufacturing Scenarios I, II and III

	SCENARIO I	SCENARIO II	SCENAIO III
REUSE	***Parts for C&W only***		
	Connecting rod	Brass fittings	Brass fittings
	Pistons	Unloaded head	Unloaded head
	Brass fittings	Standard head	Standard head
	Unloaded head	Terminal plate	Terminal plate
	Standard head	Bell housing	Bell housing
	Terminal plate	Discharge Blank Plate	Discharge Blank Plate
	Oil pump housing	Stator stack	Stator stack
	Frame	Stator lock ring	Oil pump housing
	Bell housing	Surface strainer and retaining rings	Stator lock ring
	Discharge Blank Plate	Base plate	Surface strainer and retaining rings
	Stator stack	Sump plug and spring	Base plate
	Stator lock ring	Bolts	Sump plug and spring
	Surface strainer and retaining rings	Oil suction pipe	Bolts
	Base plate	Pressure ring	Oil suction pipe
	Sump plug and spring	Stator key	Pressure ring
	Bolts	Discharge valve retaining plates	Stator key
	Gudgeon pins	Oil strainer	Discharge valve retaining plates
	Oil suction pipe		Oil strainer
	Pressure ring		
	Stator key		
	Discharge valve retaining plates		
	Oil strainer		
	Oil pump kit		
	Total weight (kg)		
	146	67	73
	Parts for C&W and Machining		
	Valve plates	Crank and bolt	Crank and bolt
	Crank and bolt		
	Total weight (kg)		
	12	10	10
	Parts for rewinding operation		
	Stator copper	Stator copper	Stator copper
	Total weight (kg)		
	7	7	7
REPLACEMENTS	***Parts replaced with new parts***		
	Piston rings	Connecting rod	Connecting rod
	Thrust washer	Pistons	Pistons
	Main bearings	Piston rings	Piston rings
	Suction Reeds	Thrust washer	Thrust washer
	Discharge reeds	Main bearings	Main bearings
		Suction Reeds	Suction Reeds
		Discharge reeds	Discharge reeds
		Gudgeon pins	Gudgeon pins
		Oil pump kit	Oil pump kit
	Total weight (kg)		
	2	6	6
	Parts replaced with pre used parts		
		Valve plates	Valve plates
		Frame	Frame
		Oil pump housing	
	Total weight (kg)		
		77	71
	Total weight of the compressor (kg)		
	167	167	167

Note: Other heavy parts like frame and valve plates (around 71 kg) are cleaned and washed (C&W) for most the time in Recom Engineering. The frame is a C&W in 95% of the time and valve plates 80% of the time.

3.2 *New (OEM) compressor versus remanufactured compressor*

Carbon footprint :The equivalent of 1,590 kg of CO_2 e- is emitted from the production of a new (OEM) 20 HP (or 15 kW) compressor. When the same compressor is remanufactured from the pre used parts of an old compressor, the GHG emissions (or carbon footprint) can be reduced to 117 kg CO_2 e-. Figure 3 shows that there will be approximately 93%, 89.5% and 89% less greenhouse gas emissions with the substitution of a new (OEM) compressor with a remanufactured compressor for Scenarios I, II and III, respectively.

Energy savings: In Scenario I, the replacement of a new (OEM) compressor with a remanufactured compressor can mitigate about 1,470 kg of CO_2 e-, which is approximately equivalent to the GHG emissions from 1.56 MWh of electricity generation in WA, and 1.71 MWh in Queensland and NSW. This electricity generation would meet the average electricity demand[1] of an Australian household for 3.5 months

Similarly, Sutherland *et al.* (2008) found that about 2.5 MWh of electricity (or equivalent to 5 months average electricity demand of an Australian household) can potentially be saved with the replacement of a new diesel engine head with a remanufactured one.

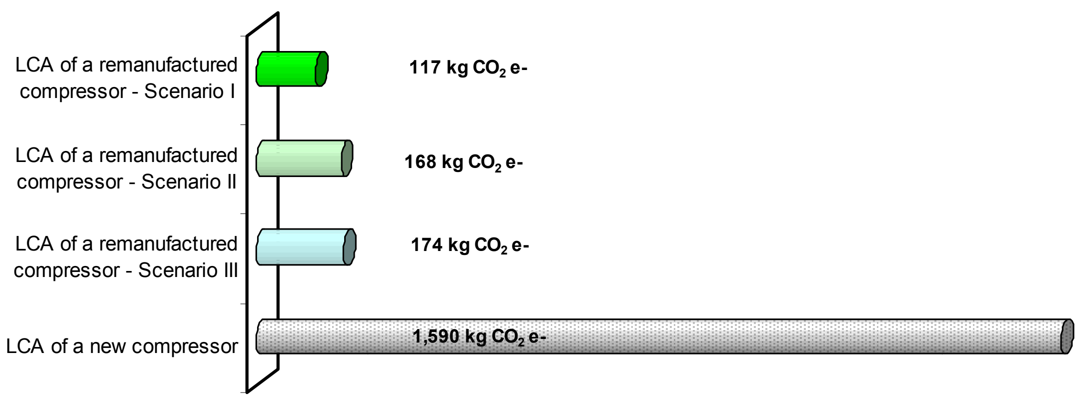


Figure 3. The Carbon footprint of a new (OEM) and remanufactured compressor for Scenarios I, II, and III.

3.3 *Identification of hotspots*

Once the total GHG emissions from the production of a new (OEM) compressor and a remanufactured compressor have been determined, the percentage distribution of greenhouse gas emissions in terms of individual production processes can be determined to identify the 'hotspots' or highly emitting process. Figures 4, 5 and 6 show the percentage distribution of greenhouse gas emissions in terms of individual production processes involved in the production of a new (OEM) compressor and a remanufactured compressor for Scenarios I and II, respectively.

In the case of the new (OEM) compressor, GHG emissions from the mining of raw metal, metal production, foundry operation, assembling and transportation were calculated. Figure 4

[1] Extrapolated from George Wilkenfeld and Associates (1998)

shows that foundry and metal processing accounted for 54% and 42% of the total GHG emissions, respectively mainly due to smelting operations. The mining of iron ore, alumina and copper accounted for only 3% of the total GHG emissions[2]. The transportation of a new (OEM) compressor from Germany to Perth would account for about (i.e. 1%) of the total GHG emissions. Scenarios I and II show how the reuse, repair and replacement of pre used parts can significantly avoid the GHG emissions resulting from the mining, processing and foundry operations associated with a manufacturing of a compressor.

In Scenario I, the rewinding process accounts for a significant (72%) portion of the total emissions during the life cycle of a remanufactured compressor (see Figure 5). This is because the rewinding process not only requires a complete replacement of copper wire. It also requires a significant amount of energy for heating and finishing purposes. In addition, only 1% of the total parts on the basis of weight are replaced with the new parts, reducing the additional emissions from the mining, processing and manufacturing processes associated with new parts. This rewinding process is regarded as the 'hotspot' in this remanufacturing scenario and therefore, could benefit from further management investigation to reduce energy consumption and the overall GHG footprint.

Although the replaced new parts only account for about 1% of the total weight of the compressor (see Table 2), the replacement with new parts was found to be the second largest GHG contributor to Scenario 1. This is because the emissions from the mining, processing and manufacturing processes of these new parts add 17.6 kg of CO_2 e- (i.e. 9%) to the emissions from the remanufacturing operations. Other significant sources of GHG emissions, resulting mainly from remanufacturing operations included: assembling and disassembling operations (7%), cleaning, washing and machining operations (5%), cleaning and washing only (4%) and testing (3%). The GHG emissions from these remanufacturing processes vary with energy consumption. The Energy consumption associated with the assembling and disassembling, cleaning, washing and machining (polishing and surface grinding) (C&W and machining), cleaning and washing only (C&W), and testing are 7.96 kWh, 5.07 kWh, 2.91 kWh and 4 kWh, respectively. Although the energy consumption associated with the testing operation is higher than that for C&W only operations, it is apparent that the GHG emissions from the testing operation are lower than the C&W only operations. This is because the emissions from the mining, processing and production of washing liquids were added to the emissions from the electricity generation for cleaning, washing and machining processes.

Figure A1 shows the process network for GHG emissions from the production of one remanufactured compressor for Scenario I. This also shows GHG emissions from the production of inputs for different stages separately.

[2] The Simapro software gave the total GHG emissions from mining through to the production of metals. The estimation of GHG emissions from metal processing and mining operations could have been more accurate if the breakdown of GHG contribution to mining and process applications was available and clearly differentiated between aluminium, cast iron, copper and steel flow trees of production.

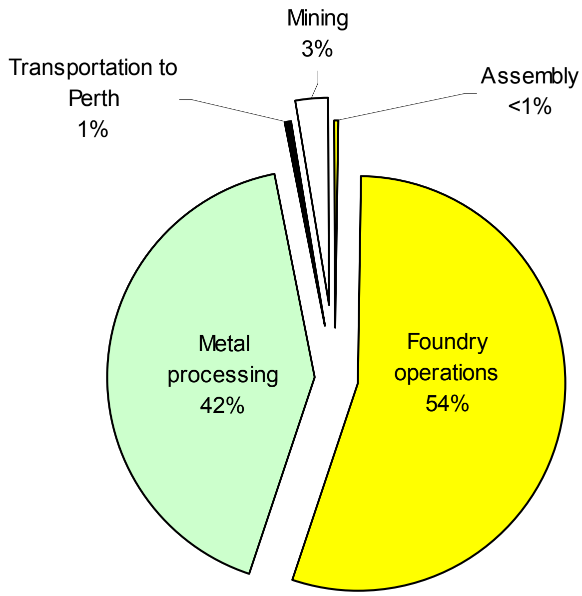


Figure 4. New (OEM) Compressor: Percentage distribution of greenhouse gas production.

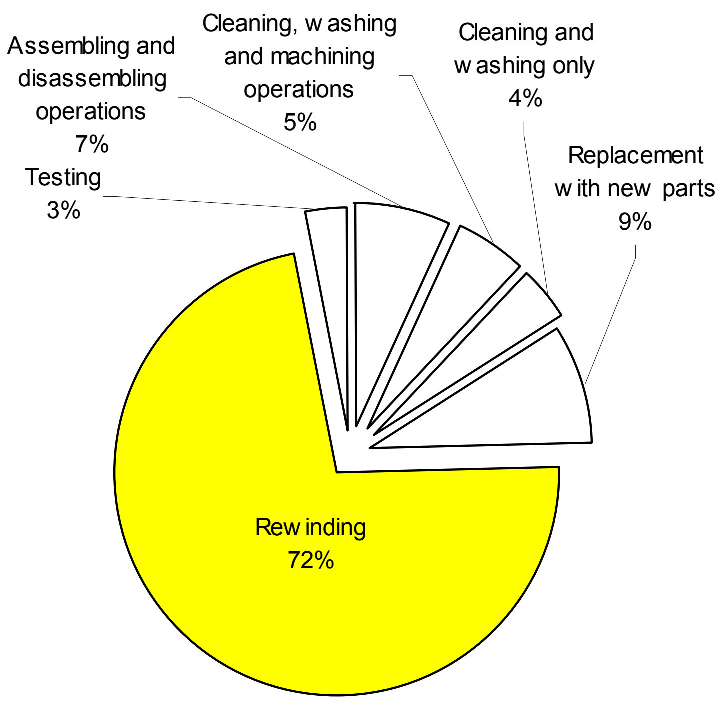


Figure 5. Remanufactured Compressor (SCENARIO I): Percentage distribution of greenhouse gas emissions.

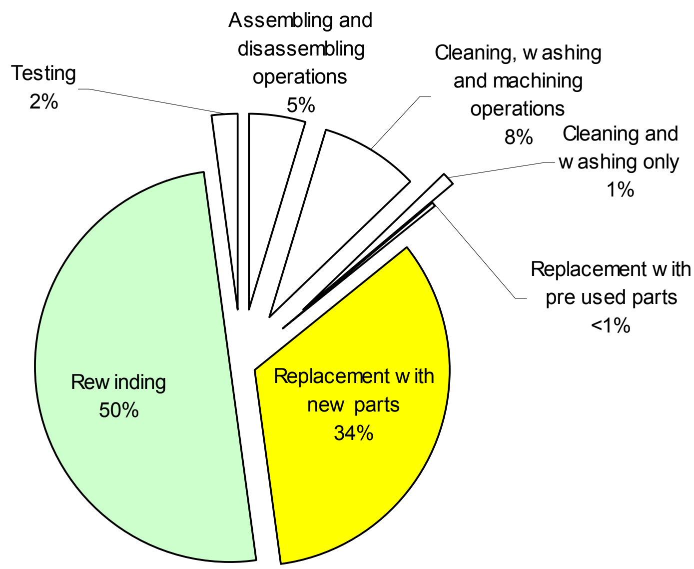


Figure 6. Remanufactured Compressor (SCENARIO II): Percentage distribution of greenhouse gas emissions.

In Scenario II, 3.5% of the compressor parts (on the basis of weight) are completely replaced with the new parts (see Table 2).

As a result, the replacement of used compressor parts with new parts accounted for a signification portion of the total CO_2 emissions (34%) (see Figure 6). About 46% of the total compressor parts were considered to be replaced with the parts from the old compressor (see Table 2), thereby significantly reducing emissions.

Figure A2 in the Appendix also shows the process network for GHG emissions from the production of one remanufactured compressor for Scenario II.

4 CONCLUSIONS

Remanufacturing can potentially significantly reduce the carbon footprint associated with the production of a new (OEM) 20 HP (or 15 kW) compressor by between 89 to 93% or 1,473 kg and 1,415 kg respectively, when 99% and 96.5% of the total parts on basis of weight are reused in remanufacturing a compressor.

The greenhouse gas savings associated with a remanufactured compressor also extend to purchase cost with a remanufactured compressor (20 HP/15 kW) some 50% cheaper than a new (OEM) compressor (David Knight, *pers. comm.*.Recom Engineering, Perth).

By comparison, a new OEM compressor produces 9.52 kg of CO_2 e- per kg of total OEM compressor unit weight (167 kg), whilst a remanufactured compressor only produces 0.7 kg of CO_2 e- per kg of remanufactured compressor unit weight (167 kg). This result in particular highlights the important value of remanufacturing in economically reducing the resource intensity and carbon footprint associated with the purchase of a compressor.

If the carbon price was set at $50 per tonne of CO_2 e-, a new (OEM) compressor would face a cost of $79.50 and a remanufactured compressor a cost of $5.85.

If it is assumed, for example, that Recom Engineering Australia wide remanufacture one hundred 20HP (15kW) compressors per year, they are contributing to overall greenhouse gas reduction by some 147.3 tonnes of CO_2 e- per year.

Whilst, the carbon footprint of a remanufactured compressor can be improved by further reducing the replacement of pre used parts with new parts, if the functional objective was extended to include the disposal of the compressor, significantly higher GHG management benefits could be achieved.

Including the final disposal of compressor units into a life cycle assessment may become an increasing reality in the industrial market as further costs and limitations are placed on the landfill disposal of industrial wastes.

In addition, as mining resources start to deplete, remanufacturing and recycling will increasingly become the norm for industrial machinery and componentry, both on an economic basis and with the need to increase greenhouse gas management of production activities in carbon constrained economies.

REFERENCES

George Wilkenfeld and Associates (1998), Household Energy Use in Australia: End Uses, Greenhouse Gas Emissions and Energy Efficiency Program Coverage, prepared for the National Appliance and Equipment Energy Efficiency Committee, accessed at http://www.energyrating.gov.au/library/pubs/hhenergy1998.pdf

ISO (1997). Environmental Management – Life Cycle Assessment – Principles and Framework, ISO 14040, International Organization for Standardization (ISO), Geneva.

Kerr, W. and Ryan, C. (2001) Eco-efficiency gains from remanufacturing A case study of photocopier remanufacturing at Fuji Xerox, Australia, Journal of Cleaner Production 9, pp. 75–81.

Neri, P, Buttol, P., Cremonini, M., Ronchi, A. and Tani A., 2000, Life Cycle Assessment of an axial air compressor manufactured by the firm Fini Compressor, Italian National Agency for New Technologies, Energy and Environment, Italy.

PRé Consultants (2008). Simapro. Version 7.1. The Netherlands.

RMIT (2005). Australian LCA database 2005. . Centre for Design, RMIT, Vic, Royal Melbourne Institute of Technology

Saha, P. K (2008) Energy efficiency improvements in Melting furnaces, Energy Saving Commission, World Foundrymen Organisation, UK.

SCLCI (2007). The Ecoinvent database. Swiss Federal Laboratories for Materials Testing and Research, Switzerland, Switch Centre for Life Cycle Inventory.

Sutherland, J. W. Daniel P. Adler, D. A., Karl R. Haapala, K. R., Kumar (2008) A comparison of manufacturing and remanufacturing energy intensities with application to diesel engine production CIRP Annals - Manufacturing Technology 57 pp 5–8.

US Department of Energy (2007) Advanced Melting Technologies: Energy Saving Concepts and Opportunities for the Metal Casting Industry, Prepared for ITP Metal Casting, US Department of Energy.

APPENDIX

Table A1. Life cycle inventory of a remanufactured compressor

Total weight of the compressor		**167 kg**					
Energy consumption in machining operations							
			Amps	voltage	time (hour)	Power (kW)	Energy (kWh)
	C&W/Compressor (pumping)		10	415	0.25		1.04
	C&W/Compressor (hotwater)		18	415	0.25		1.87
						Total	2.91
	Surface grinding/valve plate		9	415	0.33		1.23
	Polishing by lathe/crank shaft		9	415	0.25		0.93
	Spraying operation/crank						1
Copper rewinding operations							
Heating	Current		30	amps			
	Voltage		240	Volts			
	Heating time		2	hours			
	Electricity		14.4	kWh			
Rewinding	Rewinder		Amps	voltage	time (hour)	Power (kW)	Energy (kWh)
			4	240	1		0.96
Baking	Current		30	amps			
	Voltage		240	Volts			
	Baking time		2	hours			
	Electricity		14.4	kWh			
Testing/compressor							
	Power		14.92	kW			
	Testing hours		0.25	hours			
	Electricity		3.73	kWh			
Assembly/disassembly							
Disasssembling process uses handguns to separate parts, handgus are by an air compressor							
Assembling processes consumes the same energy as disassembling processes							
		HP	Time	energy			
		5	1	4			

Chemical inputs			
	CHEMICALS	Amount	Units
C&W	Alkaline	0.0667	gm/ compressor
	Phosphoric acid	0.0006	gm/ compressor
	Decarboniser	0.0006	gm/ compressor
	Thinners	100	ml/compressor
	Penetrene	50	ml/compressor
Surface grinding/day	Clear Edge EP690	0.014	l/compressor

Appendix

Part No.	Components	Pictures	Weight kg	Material composition	Reuse/replacements %	Machining operations Processes	Energy Type	Amount (kWh)	Material Name
1	Brass fittings		0.38	Brass	100%	C&W	Electricity	0.0066	Alkaline Phosphoric acid Decarboniser Thinners Penetrene
2	Unloaded head		5.3	Cast iron	100%	C&W	Electricity	0.0921	Alkaline Phosphoric acid Decarboniser Thinners Penetrene
3	Standard head		5.4	Cast iron	100%	C&W	Electricity	0.0939	Alkaline Phosphoric acid Decarboniser Thinners Penetrene
4	Valve plates		2.8	Cast iron	80%	C&W	Electricity	0.0487	Alkaline Phosphoric acid Decarboniser Thinners Penetrene
					20%	Surface grinding Replaced with old parts	Electricity	2.4651	Mineral or polyster oil Clear Edge EP690
5	Surface strainer and retaining rings		0.86	Mild stainless steel	100%	C&W	Electricity	0.0149	Alkaline Phosphoric acid Decarboniser Thinners Penetrene
6	Bolts		4	Grade 5	100%	C&W	Electricity	0.0695	Alkaline Phosphoric acid Decarboniser Thinners Penetrene
7	Gudgeon pins		0.06	Steal 4140	70%	C&W	Electricity	0.0010	Alkaline Phosphoric acid Decarboniser Thinners
					30%	Replaced with new parts			
8	Terminal plate		2.2	Cast iron	100%	C&W	Electricity	0.0382	Alkaline Phosphoric acid Decarboniser Thinners Penetrene

Appendix

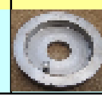
Part No.	Components	Pictures	Weight kg	Material composition	Reuse/replacements %	Machining operations Processes	Energy Type	Amount (kWh)	Material Name	Amount	Units
9	Oil pump housing		5.7	Cast iron	80%	C&W	Electricity	0.0991	Alkaline	2.27E-03	gm
									Phosphoric acid	1.89E-05	gm
									Decarboniser	1.89E-05	gm
									Thinners	3.41E+00	ml
									Penetrene	1.71E+00	ml
					10%	Replaced with new parts					
					10%	Replaced with old parts					
10	Crank and bolt		9.6	Nodular cast	70%	C&W	Electricity	0.1669	Alkaline	3.83E-03	gm
									Phosphoric acid	3.19E-05	gm
									Decarboniser	3.19E-05	gm
									Thinners	5.74E+00	ml
									Penetrene	2.87E+00	ml
									Mineral or polyster oil	0.00E+00	l
						Polishing	Electricity	0.9338			
					15%	additional grinding	Electricity	7.4700	Clear Edge EP690	0.013888889	l
					15%	additional grinding and spraying	Electricity	8.4700	Clear Edge EP690	0.013888889	l
11	Frame		68.4	Cast iron	95%	C&W	Electricity	1.1890	Alkaline	2.73E-02	gm
									Phosphoric acid	2.27E-04	gm
									Decarboniser	2.27E-04	gm
									Thinners	4.09E+01	ml
									Penetrene	2.05E+01	ml
					5%	Replaced with old parts					
12	Base plate		7.5	Mild	100%	C&W	Electricity	0.1304	Alkaline	2.99E-03	gm
									Phosphoric acid	2.49E-05	gm
									Decarboniser	2.49E-05	gm
									Thinners	4.49E+00	ml
									Penetrene	2.24E+00	ml
13	Bell housing		17.4	Cast	100%	C&W	Electricity	0.3025	Alkaline	6.94E-03	gm
									Phosphoric acid	5.78E-05	gm
									Decarboniser	5.78E-05	gm
									Thinners	1.04E+01	ml
									Penetrene	5.21E+00	ml
14	Pressure ring		0.08	Compressed steel	100%	C&W	Electricity	0.0014	Alkaline	3.19E-05	gm
									Phosphoric acid	2.66E-07	gm
									Decarboniser	2.66E-07	gm
									Thinners	4.79E-02	ml
									Penetrene	2.39E-02	ml
15	Stator key		0.04	S14	100%	C&W	Electricity	0.0007	Alkaline	1.60E-05	gm
									Phosphoric acid	1.33E-07	gm
									Decarboniser	1.33E-07	gm
									Thinners	2.39E-02	ml
									Penetrene	1.20E-02	ml
16	Oil Sight Glass		0.18	Fusite	100%	C&W	Electricity	0.0031	Alkaline	7.18E-05	gm
									Phosphoric acid	5.98E-07	gm
									Decarboniser	5.98E-07	gm
									Thinners	1.08E-01	ml
									Penetrene	5.39E-02	ml

Note: As the brass and fusite used, in making compressor oil site glass and brass fittings, only accounted for 0.4% of the total weight of the compressor, it has been excluded from the analysis.

Appendix

Part No.	Components	Pictures	Weight kg	Material composition	Reuse/replacements %	Machining operations Processes	Energy Type	Amount (kWh)	Material Name	Amount	Units
17	Oil strainer		0.04	Stainless steel	100%	C&W	Electricity	0.0007	Alkaline	1.60E-05	gm
									Phosphoric acid	1.33E-07	gm
									Decarboniser	1.33E-07	gm
									Thinners	2.39E-02	ml
									Penetrene	1.20E-02	ml
18	Discharge valve retaining plates		0.2	Steel	100%	C&W	Electricity	0.0035	Alkaline	7.98E-05	gm
									Phosphoric acid	6.65E-07	gm
									Decarboniser	6.65E-07	gm
									Thinners	1.20E-01	ml
									Penetrene	5.98E-02	ml
19	Discharge Blank Plate		0.34	Cast iron	100%	C&W	Electricity	0.0059	Alkaline	1.36E-04	gm
									Phosphoric acid	1.13E-06	gm
									Decarboniser	1.13E-06	gm
									Thinners	2.03E-01	ml
									Penetrene	1.02E-01	ml
20	Oil pump kit		1.2	En8 steel	50%	C&W	Electricity	0.0209	Alkaline	4.79E-04	gm
									Phosphoric acid	3.99E-06	gm
									Decarboniser	3.99E-06	gm
									Thinners	7.18E-01	ml
									Penetrene	3.59E-01	ml
21	Sump plug and spring		0.16	Mild steel	100%	C&W	Electricity	0.0028	Alkaline	6.38E-05	gm
									Phosphoric acid	5.32E-07	gm
									Decarboniser	5.32E-07	gm
									Thinners	9.57E-02	ml
									Penetrene	4.79E-02	ml
22	Oil suction pipe		0.18	Bundi tube	100%	C&W	Electricity	0.0031	Alkaline	7.18E-05	gm
									Phosphoric acid	5.98E-07	gm
									Decarboniser	5.98E-07	gm
									Thinners	1.08E-01	ml
									Penetrene	5.39E-02	ml
23	Main bearings		0.74	Steel/babbit	0%	Replaced with new parts					
24	Piston rings		0.6	Cast/Chrome	0%	Replaced with new parts					
25	Connecting rod		2	Aluminium	50%	C&W	Electricity	0.0348	Alkaline	7.98E-04	gm
									Phosphoric acid	6.65E-06	gm
									Decarboniser	6.65E-06	gm
									Thinners	1.20E+00	ml
									Penetrene	5.98E-01	ml
					50%	Replaced with new parts					
26	Pistons		1	Aluminium	70%	C&W	Electricity	0.0174	Alkaline	3.99E-04	gm
									Phosphoric acid	3.32E-06	gm
									Decarboniser	3.32E-06	gm
									Thinners	5.98E-01	ml
									Penetrene	2.99E-01	ml
									Mineral or polyster oil	0.00E+00	l
					30%	Replaced with new parts					
27	Suction Reeds		0.06	Steel	0%	Replaced with new parts					

Appendix

Part No.	Components	Pictures	Weight kg	Material composition	Reuse/replacements %	Machining operations Processes	Energy Type	Amount (kWh)	Material Name	Amount	Units
29	Thrust washer		0.039	Steel/Babbitt	0%	Replaced with new parts					
30	Stator copper		7.25	Copper	50%	Heating to remove cooper \	Propane - direct he	14.4	Copper	7.25	
						Rewind operation	Electricity	0.96			
						Baking	Propane - baking	14.4			
					50%	Replaced with new parts					
31	Stator stack		22.75	Swedish iron	100%	C&W	Electricity	0.40	Alkaline	9.08E-03	gm
									Phosphoric acid	7.56E-05	gm
									Decarboniser	7.56E-05	gm
									Thinners	1.36E+01	ml
									Penetrene	6.81E+00	ml
32	Gasket kit		0.4	Vulcanised fibre	0%	Replaced with new parts					
33	Stator lock ring		0.2	Mild steel	100%	C&D	Electricity	0.0035	Alkaline	7.98E-05	gm
									Phosphoric acid	6.65E-07	gm
									Decarboniser	6.65E-07	gm
									Thinners	1.20E-01	ml
									Penetrene	5.98E-02	ml

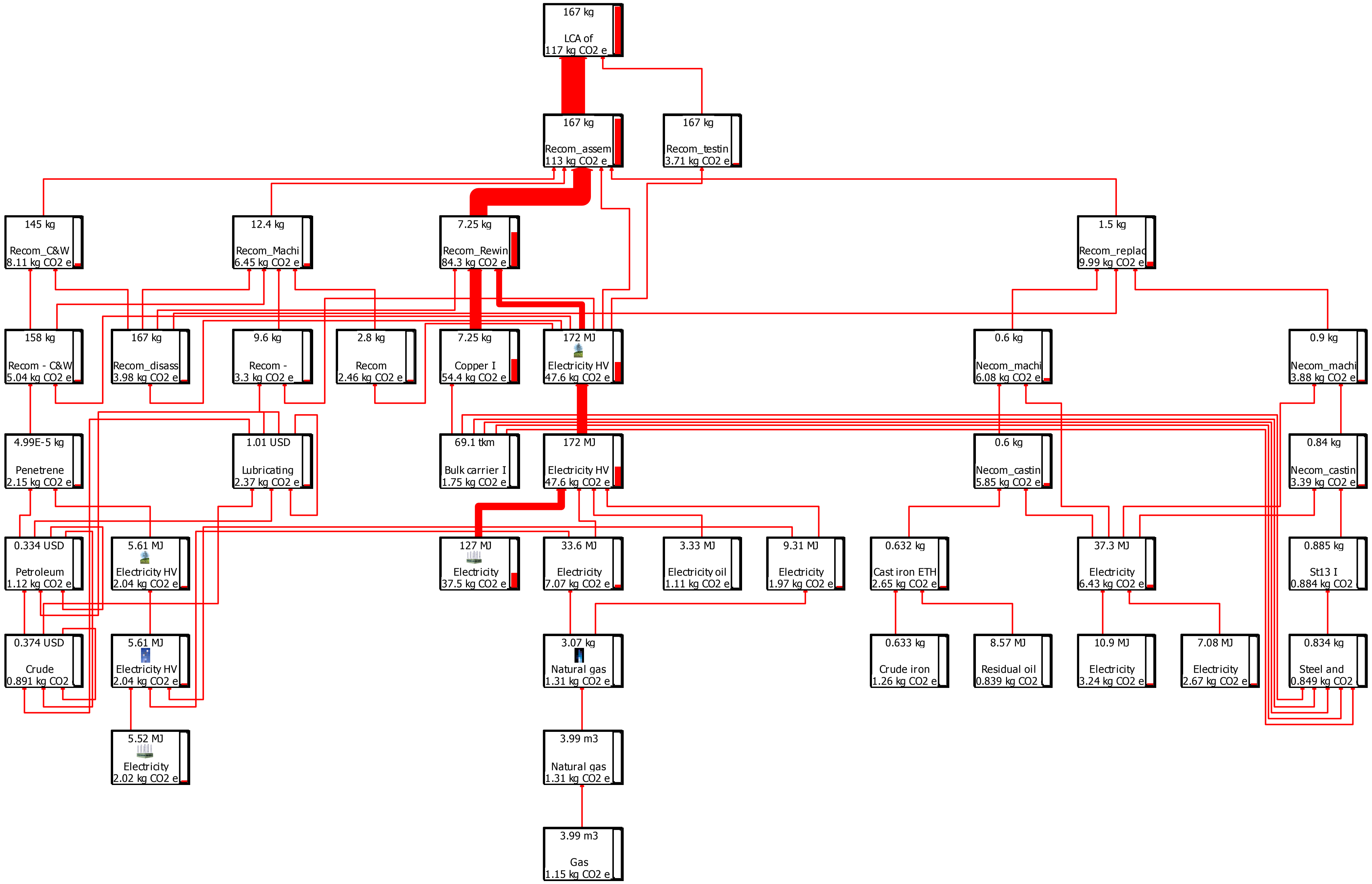


Fig A1 Process network showing GHG emissions from the production of a remanufactured compressor in Scenario I

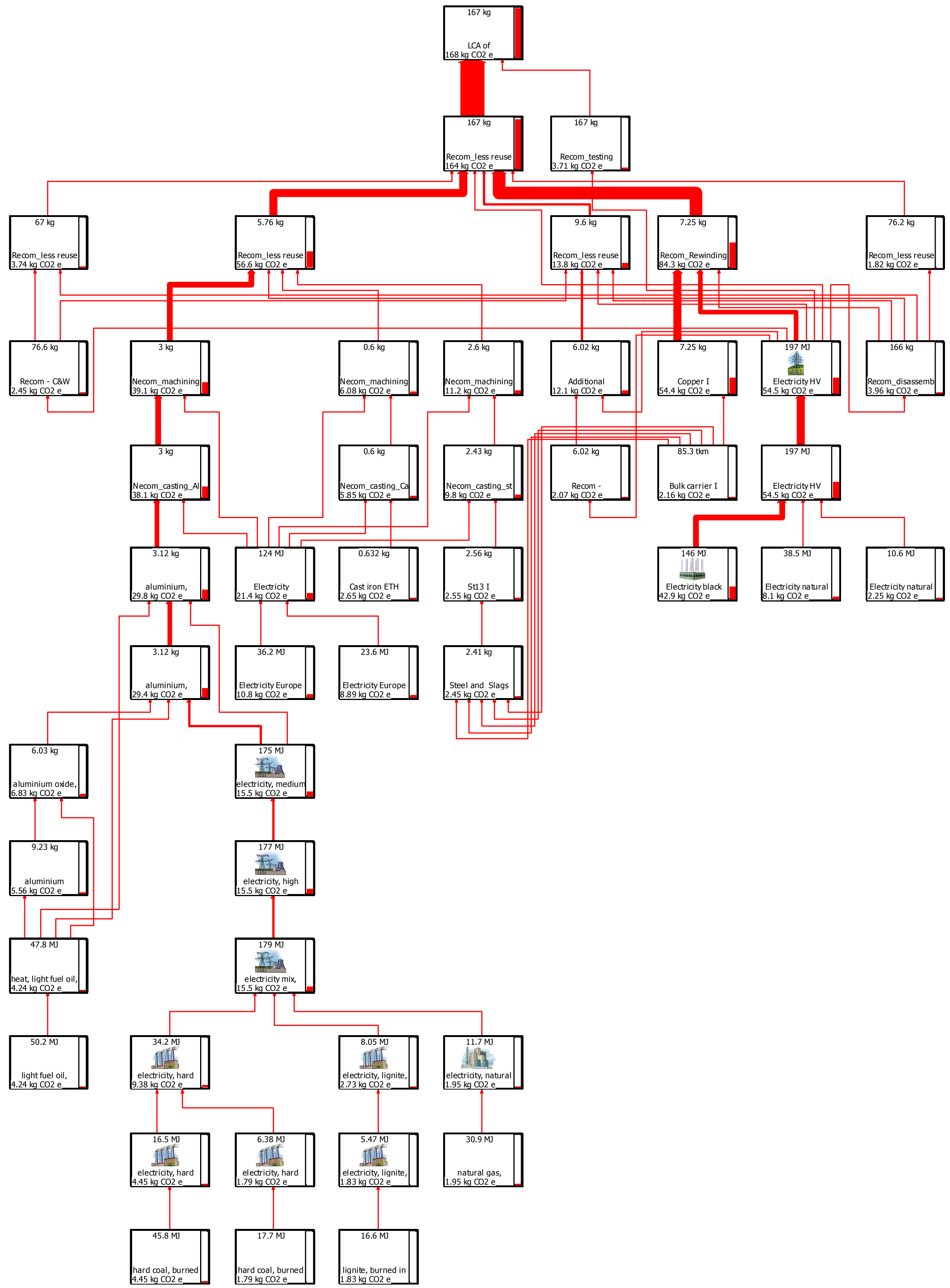


Fig A2 Process network showing GHG emissions from the production of a remanufactured compressor in Scenario II.