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Abstract

Operational energy use in buildings~~,~~ accounts for 28% of global energy demand. One method to reduce operational energy is upgrading old appliances to more efficient ones. In Australia, the most common residential heating type is reverse-cycle heating, followed by gas heating.

This research paper aims to determine the energy balance resulting from a gas heating upgrade through a life cycle assessment (LCA). Extensive primary data was collected for operational energy performance of 61 ducted gas heating upgrades. To address the scarcity of data on material composition, one ducted gas heater was deconstructed and assessed in terms of material composition (types and weights). The comparison between embodied energy and operational energy savings allows us to establish whether operational energy savings offset the embodied energy incurred with the upgrade.

The end of life stage of the old appliance, as well as the production, construction and use stage of the new appliance were assessed. Results show that operational energy savings offset the following impact categories: global warming, ozone layer depletion, aquatic acidification, non-renewable energy, and carcinogens. Only the mineral extraction is not offset by the operational energy savings. Results clearly demonstrate that operational energy savings outweigh the embodied energy and therefore contribute positively to the environment.

This study is the first to focus on the LCA of building services through extensive primary data collection and a focus on a high number of appliances. This supports ongoing energy efficient upgrades in Australia and pave the way for further, similar studies to confirm or disprove these findings in other parts of the world.

Keywords: Building services, Ducted gas heater, Gas heating, Life cycle Assessment, Embodied energy, operational energy, primary data

1. Introduction

Buildings account for more than 40% of global energy demand and nearly one third of global greenhouse gas (GHG) emissions [1-3], therefore it is important to address the significant environmental impacts of buildings and construction by evaluating buildings and their components through a whole-life ~~based~~ lens [4].

To lower carbon emissions produced by existing buildings, energy efficient refurbishment is one solution, predominantly when considering that buildings have long lifespans and that often the structure is sound enough to warrant ~~an~~ extending~~ed~~ the ~~life to a~~ building's lifespan [5-7]. In this regard, improving energy efficiency of existing buildings can strengthen the energy security worldwide and lower carbon emissions. The life cycle of refurbishment measures is principally used to assess both the materials to be added to existing building and the energy consumption patterns of users [8].

~~Globally the energy efficiency of buildings improved by just 13% between 2000 and 2016 and the International Energy Agency has given a warning that without governments designing and implementing new policies, the environmental impact of buildings will increase further [3]. It is estimated that out of all construction activity rennovations account for 57% but currently the annual building stock renovation only lies at about 1- 2% [9]. To lower carbon emissions produced by existing buildings, energy efficient refurbishment is one solution, predominantly when considering that buildings have long lifespans and that often the structure is sound enough to warrant an extended life to a building [5-7]. In this regard, improving energy efficiency of existing buildings can strengthen the energy security worldwide and lower carbon emissions. There is plenty of literature regarding the effectiveness of energy efficiency refurbishment measures from a cost-benefit perspective [10-13]. Nevertheless, the use of LCAs of energy efficient refurbishments in the building sector is less common [14]. The life cycle of refurbishment measures should principally assess both the materials to be added to the existing building and the energy consumption patterns of users [8]. Nonetheless, there is a lack of transparency and available energy data for a building over its life cycle and even less research on sustainable refurbishment [15].~~

When considering the entire life of a building, operational energy is often considered the most relevant part of the building's life cycle [16-19]. The operational energy is used to heat, cool, ventilate and power appliances within the building. Embodied energy is the energy required through processes of producing buildings materials [20] and ~~complements~~ when combined with operational energy, can be assessed via a ~~to achieve a~~ whole-of-life approach. The Australian Capital Territory (ACT) Government has capitalized on the potential of reducing energy consumption in homes and businesses and introduced in 2013 the Energy Efficiency Improvement Scheme (EEIS) [21]. The scheme puts an energy saving obligation on retailers which requires that large retailers undertake approved energy saving initiatives while smaller retailers have the option to deliver initiatives or pay a contribution to fund those initiatives [22]. The energy saving activities under the EEIS include, inter alia, upgrading old ducted gas heaters to more efficient appliances. ~~One common method to reduce operational energy is the upgrade of old appliances with more efficient ones. When considering energy efficiency upgrades, space heating and domestic water contribute significantly to the operational energy consumption of a residential building. Heating makes up for around 20% to 50% of a buildings energy consumption wherefore domestic hot water makes up for around 10% to 20% [23].~~ This energy saving activity seems to have a great energy saving potential, as ~~I~~in Australia, the most common residential heating type is reverse-cycle heating, followed by gas heating [24]. Furthermore, heating makes up for around 20% to 50% of a building's energy consumption [23]. The question arises what potential benefits can result from a heating upgrade? Therefore, the research paper aims to answer the following questions:

~~One gas heating solution is a ducted gas heating system which is widely used in Australia. A ducted gas heating unit can be used as single heating system for an entire house. It is connected to ducts through which the heated air goes to the duct outlets into the open space. The ducted gas heater can be installed under the flooring or in the roof cavity.~~

~~This research paper aims to assess the life cycle of a ducted gas heater in the Australian Capital Territory (ACT), Australia, from cradle-to-grave and aims to answer the following research questions:~~

- How much operational energy can be saved through a ducted gas heating upgrade, and can the overall environmental footprint be lowered?
- ~~What is the environmental footprint of a ducted gas heater?~~
- Do the resulting operational energy savings from replacing ducted gas heaters offset the embodied energy of the new appliance?

To answer these questions, a reference ducted gas heater has been deconstructed and assessed for its materials. A dataset of old and new appliances has~~d~~ then been assessed and compared over their life cycles. The operational energy savings have been taken into account as well, to estimate if the savings offset the environmental impacts of the upgrade. This paper is aiming to help decision makers make a conscious and informed decision on the implementation of ducted gas heating upgrades while considering the whole life cycle impacts. It furthermore attempts to identify further potential benefits of a heating upgrade.

The next section reviews literature of LCA studies assessing building heating and cooling appliances. Section 3 presents the research design and methodology, while Section 4 presents the results of the LCA which are discussion in Section 5. Section 6 concludes the research paper.

2. Literature Review

To ensure no duplications and highlight the necessity of this study~~in undertaking research and highlighting the necessity for this study~~, a literature review was conducted. Due to fast changes in technology the current literature of the last ten years was systemically reviewed. The systematic approach was used to ensure studies were selected objectively without omitting relevant literature and to ignore~~ignoring~~ irrelevant publications.

Therefore, Web of Knowledge was ~~(to cover academic literature) and Google Scholar (to also capture potentially relevant grey literature) were~~ used to identify studies with the following key words:

- energy efficiency;
- residential building;
- life cycle assessment (LCA);
- retrofit;
- refurbishment;
- heating and cooling;
- building service;
- building appliances;
- heating appliance; and
- HVAC system.~~;~~

A combination of several ~~of the~~ key words was used to find literature regarding LCAs on residential retrofits, energy efficiency upgrades and LCAs on heating and cooling upgrades. The results showed that there is only limited research available to considering the life cycle of explicitly heating and cooling upgrades, meaning replacing an old heating and cooling appliance with a new one~~upgrades~~.

2.1. Life Cycle Assessment

An LCA is the assessment of environmental impacts of a product, process or service ~~during~~ over its whole life (from cradle to grave) and became a commonly used tool over the years [3]. Significantly, LCA offers the possibility to compare different products and simply pinpoint opportunities of improvement. Also, the consideration of all stages of a product or service and the exposing of data make LCA a commonly used methodology [25].
In accordance with ISO 14040, an LCA consists of defining the goal and scope, creating the life cycle inventory, assessing the impact and finally interpreting the results [26]. The assessment commonly includes the entire life cycle from raw material extraction, manufacturing, construction, operation and maintenance to the end-of-life (demolition, disposal, reuse and recycling) [4, 27]. Common impact categories assessed during the life cycle of a product are global warming potential (GWP), depletion of minerals and fossil fuels, photochemical oxidation (smog), human toxicity, ozone depletion, eutrophication, water use, land use, acidification and ecotoxicity [4].

2.2. Life cycle of building appliances

The residential sector offers a significant potential for energy savings [28] and there is currently plenty of literature available which separately examines LCAs, residential building retrofits and heating systems. However, when looking at these three research fields combined, relevant literature is limited. Hence, strategies and policy efforts should focus on encouraging architects, developers, builders and household residents to seek sustainable ways of creating comfortable homes whilst minimising environmental impacts.

Most of the literature assessed considers the building envelope as a retrofitting strategy whereby heating systems are only considered from an operational point of view and rarely as part of a whole LCA. The consequences of such shortcomings are well evidenced by the recent landmark publication from the UK's Chartered Institute of Building Services Engineers (CIBSE), which represents a world-first methodology for the life cycle assessment of building services [29]. Certain energy efficiency upgrades like building insulation may reduce operational energy but significantly increase a building's embodied energy [30]. When investing in energy-efficient and low-carbon intensity ~~intensive~~ heating and cooling technologies, the final energy demand in buildings could be reduced by 25% [3]. In a scenario where a building has greater energy efficiency appliances, the largest environmental impact might reside in the production phase of the product [31].

Hence, it is important to ~~also~~ look at the life cycle of heating and cooling appliances. This literature review therefore focuses ~~exclusively~~ on the literature available which examines the complete life cycle of heating and cooling systems. The available literature is listed in

Table 1, listing each life cycle stage investigated in accordance with the BS EN 15978:201 which is a European Standard to assess the life cycle of new or refurbished buildings. Furthermore, the table list ~~and~~ the type of heating and cooling system.
There is only limited literature available on energy efficient heating and cooling upgrades. LCAs of building services are rare, with the exception of solar heaters that have been analysed from a life cycle perspective [32, 33]. Moreover, ~~T~~the research is primarily limited to gas or electric heating, heat recovery and mechanical ventilation, air conditioning, heat pumps and multiple heating systems.

Authors	Country	Heating system(s)		BS EN 15978:2011 Life Cycle Stages																
		Old	New	A 1	A 2	A 3	A 4	A 5	B 1	B 2	B 3	B 4	B 5	B 6	B 7	C 1	C 2	C 3	C 4	D
[34]	Turkey	Gas boiler and coal boiler	▪ Heat pump	x	x		x	x		x				x			x		x	
[35]	Saudi Arabia		▪ Air conditioning	x	x	x	x							x					x	
[36]	Germany	Baseline Scenario	▪ Natural gas boiler ▪ Infrared system ▪ Heat pump ▪ Electric baseboards ▪ Oil boiler	x	x		x	x						x		x			x	
[37]	Italy	N.A.	▪ Gas fired heater ▪ Gas fired autonomous heater ▪ Air conditioning (office building)			x	x	x						x			x		x	x
[38]	UK	Gas boiler	▪ Ground source heat pumps (GSHP) (air, ground and water)	x	x	x	x	x		x				x			x		x	x
[39]	China	N.A.	▪ Centralized air conditioning ▪ Split air conditioning	x	x	x	x	x					x	x		x	x			
[40]	N.A.	N.A.	▪ Air conditioning	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	
[41]		N.A.	▪ Space Heating and Cooling	x		x					x	x	x	x	x	x		x	x	

Authors	Country	Heating system(s)		BS EN 15978:2011 Life Cycle Stages																
		Old	New	A 1	A 2	A 3	A 4	A 5	B 1	B 2	B 3	B 4	B 5	B 6	B 7	C 1	C 2	C 3	C 4	D
[42]	Finland	Electric heating	▪ Air-source heat pump (ASHP) ▪ Novel ground-source air heat pump	x	x	x	x							x				x	x	
[28]	Canada	Baseboard heating	▪ Gas furnace ▪ Wood pellet stove ▪ Envelope conforming to the national building code 2015 (NBC+R) ▪ Envelope conforming to the Novoclimat1 2.0 program ▪ ASHP ▪ Combined scenario with improved insulation and ASHP (Novo+ASHP) and ▪ GSHP.							x				x		x		x	x	
[43]	Sweden	Mechanic ventilation	▪ Mechanic ventilation ▪ Heat recovery ventilation	x	x	x	x	x		x	x	x	x	x		x	x	x	x	
[44]	US	N.A.	▪ Central natural gas furnace heating and	x		x	x							x					x	x

Authors	Country	Heating system(s)		BS EN 15978:2011 Life Cycle Stages																
		Old	New	A 1	A 2	A 3	A 4	A 5	B 1	B 2	B 3	B 4	B 5	B 6	B 7	C 1	C 2	C 3	C 4	D
			conventional central air-conditioning ▪ Natural gas-powered hydronic heating and conventional central air-conditioning ▪ Electric air–air heat pump for heating as well as cooling.																	
[45]	France	N.A.	▪ Electric heat pump ▪ Wood pellet condensing boiler ▪ Wood pellet micro-cogeneration unit ▪ District heating			x		x		x				x		x		x		
[46]	UK	Gas boiler	▪ Hybrid Heat pump	x	x	x	x			x				x	x		x	x	x	x
[47]	Italy	N.A.	▪ Combi boiler (air and propane) ▪ Condensing boiler (gas)	x	x	x	x							x					x	

Table 1: *List of literature assessing heating and cooling appliances*

2.2.1. Life cycle of heating appliance

Thiers and Peuportier [45] compare different heating systems and the thermal comfort of different building types; two attached passive houses and a renovated apartment complex. The apartment complex has a significantly higher consumption, which relates to the larger floor area. The results of the LCA show that the heat pump and micro-cogeneration system are higher for the apartment complex in most of the assessed categories, except ecotoxicity, human health and odour [45]. It is worth mentioning, that the focus of the research was not on the heating system itself but rather on the energy performance of the building. Therefore, the embodied energy of the heating systems was not assessed. ~~It can be assumed that the impact per capita is lower as the apartment complex tends to hold more people. The findings of~~ Asdrubali, Baldassarri and Fthenakis [37] also predominately focus on the overall performance of the building than the heating appliances. The findings of the above research show that an energy efficiency upgrade in a detached house has a lower environmental impact then in a multi-story house. This may be the result of having one system for the detached building in comparison to several systems for the multi-complex building. Ramírez-Villegas, Eriksson and Olofsson [43] also modelled energy efficiency in combination with wall insulation. Again, the energy consumption has been modelled and does not rely on real data. These have been modelled with a building energy simulation tool (EQUA, 2013). While modelling different temperature settings, the environmental impact varies for each energy efficiency upgrade. This makes it hard to compare a change in temperature and will consequently result in an increase of electricity; causing a higher environmental impact [48]. The study's authors advise on keeping energy setpoints constant to ensure an accurate comparison.

Lin et al. [46] assessed the life cycle of a gas boiler and a hybrid heat pump via an LCA. The SimaPro 8.0 software was used to assess 14 impact categories via the Ecoinvent v3 database. The assessed stages of the two boilers are heavily based on assumptions. The energy data are based on the recommendation of the manufacturer and do not include behavioural tendencies of the users. A sensitivity analysis was conducted, the findings had shown that the global warming potential is 30% to 40% lower for the hybrid heat pump. The impacts of the gas boiler were only higher for the human toxicity, water depletion and metal depletion. However, this study heavily relied on secondary data, a larger scale of energy consumption data would be recommended to have a real representation of the operational energy usage. Vignali [47] assessed the life cycle of a conventional gas boiler and a condensing boiler in three different locations in Italy and for two types of dwellings. The inventory data for components and packaging were provided by the manufacturer and Ecoinvent was used as secondary source of data. SimaPro version 7.3.3 was used to calculate via CML2001 the life cycle impacts. The boilers were assessed on six impact categories (Acidification Potential, Eutrophication Potential, Global Warming Potential for a time horizon of 100 years, Photochemical Ozone Creation Potential, Stratospheric Ozone Depletion Potential and Cumulative Energy Demand) for both dwellings in three locations in Italy. Also, have the same stages been considered for both boilers which makes a comparison reasonable. The energy consumption is not based on primary data, but on the efficiency of the boilers in different scenarios. The findings had shown that the impacts of the condensing boiler were 30 % lower for the acidification potential, 48% for the eutrophication potential and 24% for the photochemical ozone creation potential. The impacts of the condensing boiler were also 15% lower for energy demand, global warming, and ozone depletion potential. Vignali also states, that the environmental sustainability of boilers can be improved by optimizing the energy efficiency of these systems [47].

2.2.2. Life cycle of heating and cooling appliance

Li [40] assesses the environmental impact of an air conditioner via the Ingersoll Rand's (IR) Screening LCA tool, which is not commonly used. Four impact categories (Global Warming Potential, Acidification Potential, Eutrophication Potential and Ozone Depletion Potential) have been assessed in total. The material compostion shows that both air conditioners predominately consist of carbon steel (aprox. 47%), aluminum (aprox. 10%) and ferrous (aprox. 17%). The real origin of the material information stays unclear. The energy data are based on modelling and results in ~~and finds out that~~ 70% of the environmental impact coming~~es~~ from ~~the~~ operational energy use. Therefore it would be ideal to base the energy consumption on real data. The second highest contributer to the environmental impacts is ~~followed by~~ the refrigerant leakage. The raw materials which are predominately steel and aluminium ~~only~~ have only a minor impact. [40]. The LCA section of the paper is kept relatively short and some origins of the data stay unclear. Also the research does not give detailed information on the material composition, the share can only be seen in graphs.

Asdrubali, Baldassarri and Fthenakis [37], ~~Hu and Zheng~~ [39]~~,~~ Pedinotti-castelle et al [28] and Ramírez-Villegas, Eriksson and Olofsson [43] only consider a heating (and cooling) upgrade in combination with other energy efficient retrofits like the upgrade of the building envelope. Asdrubali, Baldassarri and Fthenakis [37] investigate the upgrade of a gas fired heating system for three different types of buildings via an LCA but most of the data is based on assumptions like the energy consumption of the building and the buildings are difficult to compare due to different sizing. It would be relevant to break the impact down per capita, as the floor area and number of occupants is different; allowing for more accurate analysis [49, 50].

2.2.3. Life cycle of heating and cooling retrofits

Hu and Zheng [39] investigate the impact of a centralized split air conditioner in a short research paper. The values represented in the research paper have no further information provided of its origin. Ramírez-Villegas, Eriksson and Olofsson [43] only consider an air conditioner for an office building wherefore the results cannot be compared [28]. The same problem can be found for heat recovery and natural ventilation systems. The only heating system which has been broadly examined in literature is the heat pump. The heat pump retrofits in this literature review predominantly were compared to gas boiler heaters. The main findings from literature all agree that the heat pump has larger environmental impacts than a gas boiler. This is primarily due to the grid electricity mix and less a result of endogenous traits of each system [37, 44]. Almutairi et al. assesses the life cycle of an air conditioner. The air conditioner is split by its material and the electricity composition of Saudi Arabia is assessed. The study clearly states that the operational energy use has the highest impact due to the high use of fossil fuels in Saudi Arabi [35].

Greening and Azapagic [38] assessed the life cycle impacts of an air, ground, surface water and groundwater source heat pump in comparison to a gas boiler for the residential building sector. While using GaBi v. 4.4, the environmental impacts (Abiotic resource depletion of elements, Abiotic resource depletion of fossil fuels, Acidification potential, Eutrophication potential, fresh water aquatic ecotoxicity potential, Global warming potential, Human toxicity potential, Marine aquatic ecotoxicity potential, Ozone layer depletion potential and Photochemical ozone creation) were assessed with the CML 2 Baseline 2001 methodology. Nevertheless, maintenance and installation has not been considered for the gas boiler wherby it was for the heat pump systems. This reduces the comparability. Data on the material, installation and infrastructure of the appliance were sourced from manufacturers, contractors and operators. The study demonstrated that ground and water source heat pumps perform better than air source heat pumps. This is due to the lower efficiency rating of the air source heat pumps, as the main contributer is the operating energy. Even with a sufficiently decarbonised electricity grid will the life cycle impacts of the heat pump be higher. ~~found that the heat pump has higher impacts in all assessed categories during the life cycle except for global warming potential and abiotic resource depletion of elements.~~ Abusoglu and Sedeeq [34] used an exergo-environmental analysis to compare the energetic, exergetic and environmental performance of a ground source heat pump with a conventional coal and gas fired heating system. Material data were sourced from the manufacturer and Ecoinvent. Only the components and corresponding weights of the appliances have been shared but the split of data from the manufacturer and Ecoinvent is not visible. The impact categories were assessed via SimaPro v.7.1 and the IMPACT 2002+ analysis was selected. The results state that the ground source heat pump has a better energetic and exergetic efficiency than the fuel powered boilers, due to the minimum exergy destruction. Nonetheless, the environmental impact is the highest for the ground source heat pump, similar to the findings of Greening and Azapagic. Abusoglu and Sedeeq state that this is due to the use of copper and the R-134a refrigerant which needs an annual maintenance of 0.1 kg. Furthermore, the impact of the heat pump with ~~conducted further analysis of an~~ 80% renewable electricity grid was conducted and the heat pump still had higher environmental impacts. Nonetheless, the study examined by Abusoglu and Sedeeq [34] does not consider the same scope for the heating upgrade as for the existing heater. Hence, the heat pump includes the installation and maintenance of the system, which has been excluded for the fossil fuel boiler. Also, the fossil fuel boiler system heats via radiators while the ground source heat pump heats via floor heating. This false comparison impacts the life cycle results, as more stages have been included for the upgrade which consequently have a higher impact. Only Shah,

Shah, Debella and Ries [44] consider a gas heater in combination with an air conditioner, as the heat pump also provides cooling in summer. Even when comparing the heat pump with a gas heater in combination with an air conditioner, the heat pump has higher environmental impacts which can be linked to the grid electricity mix. The environmental impacts of the heat pump have been shown to only be higher in regions with higher proportions of fossil fuels in their grid electricity mix. Therefore, the study of Shah, Debella and Ries [44] contradicts Abusoglu's and Sedeeq's [34] study. In comparison with an electric heater, the heat pump is a more environmental friendly option [36, 42]. In a similar vein, Mattinen et al. [42] found that due to digging and drilling for pipes of the ground source heat pump, the air source heat pump is easier to install but that the ground source heat pump is the most environmentally-friendly solution when considering the greenhouse gas emissions produced during its life cycle. All studies are based on assumptions for the operational use and show a need for real data on operational energy prior to and ~~after~~ post a heating and cooling upgrade.

2.2.4. ~~Recap~~Summary

Examination of the literature uncovered a dearth of studies covering the embodied energy of refurbishments involving the replacement/upgrade of heating and cooling appliances [40]. This is due to the difficulty of evaluating the mechanics of the appliance and the rather low impact of carbon emissions during the manufacturing process in comparison to the carbon emissions produced during operational use [51]. The life cycle stages which have been considered by Li [40], Longo~~, S.,~~ et al. [41] and Ramirez-Villegas et al.~~, R., O. Eriksson, and T. Olofsson~~ [43] whereby other authors appear~~do seem~~ to focus on distinct ~~particular~~ stages. It can be seen in

Table 1 shows that there is a focus on A1, A3, A4 and B6, whereby B7, D, B4 and B3 are more frequently ~~not as commonly~~ disregarded~~assessed~~. Also, most research focuses on Europe, Turkey, Saudi Arabia, the US and China. No studies focus on Australia.

This literature review illustrated that there is a gap in literature available assessing the life cycle of heating and cooling retrofits and that there is in particular a gap in literature on Australia. Additionally, the identified studies compare different heating systems; leading to difficulty in comparing and verifying results. The heat pump appears the most examined system followed by the gas heater, as it can be seen in

Table 1. Additionally, most studies are based on assumptions and do not take into consideration energy consumption prior and after to the retrofit. All studies are based on energy consumption modelling. There is a need for real data to make stronger statements about the savings generated from heating and cooling upgrades and if these offset the environmental impact of the production, construction and end of life stages. Furthermore, current research is based on a small spectrum of appliances. Varying consumer behaviour can have a large impact on the operational energy. While bringing energy efficiency upgrades on scale, a more precise statement can be made if this energy efficiency upgrade is beneficial. The large amount of assumptions therefore makes it hard for decision makers to apply the theory in practice. It is recommended to use more primary data and ensure accurate findings to limit ~~mistake~~ error rates. Furthermore, the current research is commonly only backed up with a small set of data, whereby especially energy consumption data would benefit from a larger set of data to eliminate energy behaviour. There is a demonstrated gap in research in LCAs of energy efficiency upgrades for heating and cooling appliances. This gap is worth exploring in future research.

3. Research design, methods and data ~~Research Methodology and design~~ ~~Methodology and data~~

~~3.~~ This section introduces the LCA methodology with its goal and scope, the methods used in the research as well as the input data used.

3.1. Goal and scope

The goal of this study was to determine if the energy savings from replacing a ducted gas heating system with a more efficient six-star energy rated ducted gas heating system will outweigh the embodied energy. The assessment was conducted in alignment with the stages of the BS EN 15978-2011 and the ISO 14040 guidelines. The European Standard outlines the calculation method to assess the environmental performance of new or refurbished buildings based on their life cycle and quantified environmental information. The scope of the study ranged ~~from the extraction of the raw material,~~from the extraction of the raw material to transport, to manufacturing and use of the new appliance to the disposal and transportion of the old appliance (see Table 2). Other stages have been excluded due to the lack of data and to avoid distorting the results based exclusively on assumptions. The Deconstruction and C~~c~~onstruction – installation process was excluded as the deconstruction and installation of the ducted gas heating system does not require heavy machinery.

Craftsmen tools were used and occasionally ramps to lift the appliance to the cavity of the ceiling. As there has been no data available for which appliance needed lifting and which exact appliances were used it has been considered that no accurate assumptions can be made to be considered. ~~has only a minor impact and is therefore not relevant.~~ The installation company advised that the maintenance, repair, replacement, and refurbishment requests could not be recorded in sufficient detail (relevant for this research paper), as the customers had the choice of either going to the installation company or the manufacturer directly. Data from the manufacturer could not been sought. Hence, to not impact the results these stages have not been considered. The operational water use does not apply to the ducted gas heating system and has therefore not been included. Waste processing has been further excluded, as details about the waste processing facility were not available. The scope includes consideration of global warming, ozone layer depletion, aquatic acidification, non-renewable energy, mineral extraction and carcinogens categories.

LIFE CYCLE ASSESSMENT

PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARY
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw Material Supply	Transport	Manufacturing	Transport	Construction - installation-process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction	Transport	Waste processing	Disposal	Reuse, Recovery, Recycling-potential
x	x	x	x							x			x		x	

Table 2: Life Cycle Assessment - based on BS EN 15978-2011. Life cycle stages marked with an X are included in this research

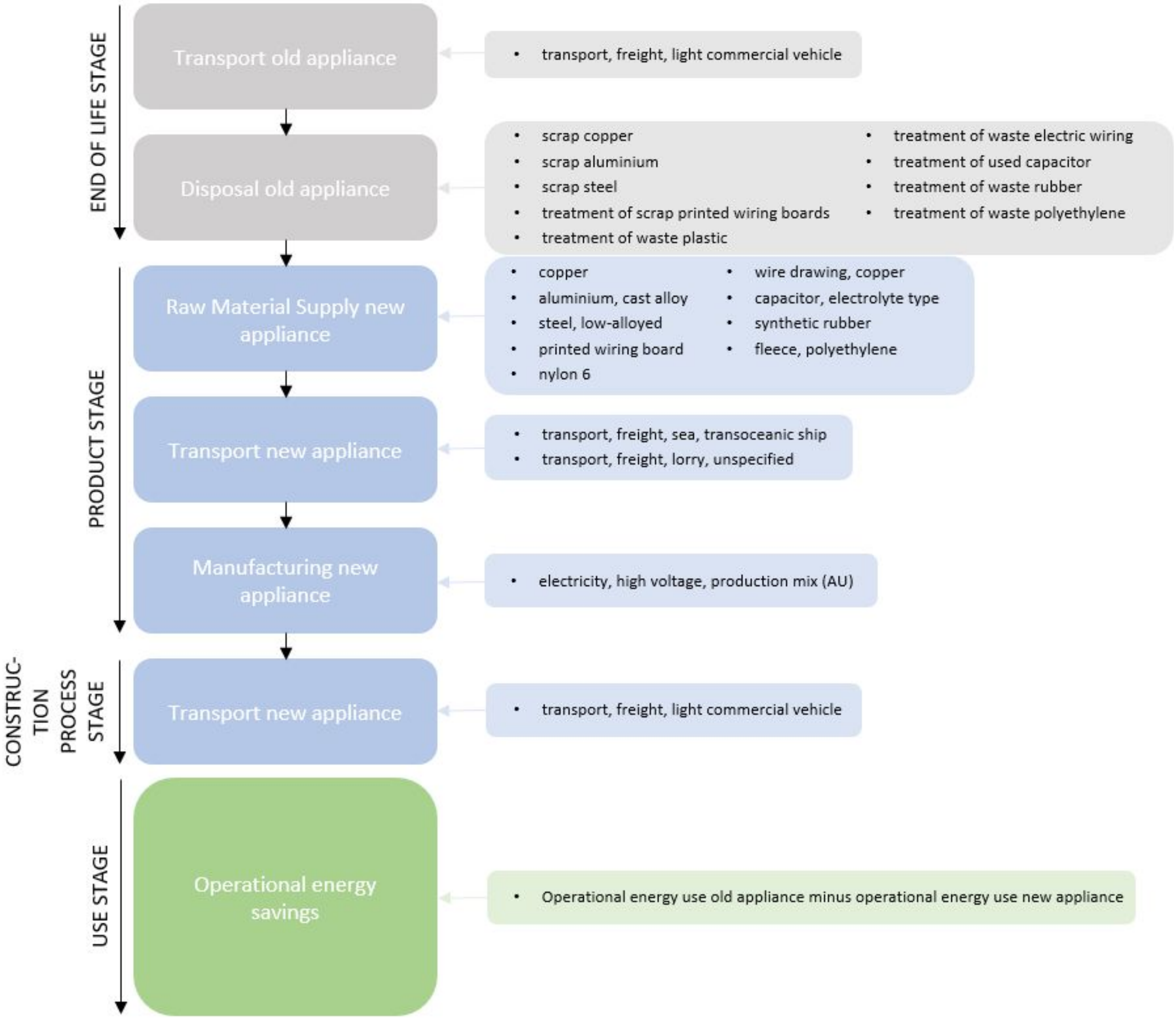
3.2. Methods

As this study evaluates energy savings from interchanging an old energy appliance to a ~~new energy~~ appliance more efficient (six-star energy rated), a Life Cycle Assessment (LCA) approach was considered as the most suitable procedure to determine the environmental impact and the offsets of the new ducted gas heater. It further was enhanced by calculating the material composition and operational energy savings via Excel based on a distinguished assessment of a reference ducted gas heater and a source of energy data. ~~The assessment was conducted in alignment with the stages of the BS EN 15978-2011 and the ISO 14040 guidelines.~~ The quality of the available data was scrutinised and assessed in detail. The data set consisted of 289 ducted gas heating upgrades and was linked to the properties' energy consumption. Only 107 properties that had received a ducted gas heating upgrade could be linked to energy consumption data of one year prior and after the heating upgrade. Energy consumption data which had no full year of energy data one year prior and after the upgrade were excluded. This includes any data which had been a false report within the year, meaning the gas meter was corrected. Of the remaining 107 ducted gas heating upgrades, the information provided from the old ducted gas heaters were assessed. As there were some relatively old ducted gas heaters, the brand and model numbers were not identifiable. Therefore, the weight of the old appliance could not be identified and the upgrade was excluded. That left 61 ducted gas heating upgrades which contains a full set of energy data one year prior and after the upgrade as well as information on the brand and model of the old appliance. The brand and model of the new appliance was provided for all ducted gas heating upgrades. The goal and scope definition of the assessed system was conducted in accordance with BS EN 15978-2011 and ISO 14040 recommendations ~~The goal and scope definition of the assessed system was conducted in according to ISO 14040 recommendations~~ [26]. *OpenLCA* software was used to assess the old and new appliances. The *Ecoinvent 3.4 cut-off* database was used as the primary source for the life cycle inventory (LCI) and primary energy saving data of the old and new ducted gas heating appliance were calculated in *Excel* and fed into *OpenLCA.* The system flow "heat, central or small-scale, natural gas" with the unit process "market for heat, central or small-scale, natural gas | heat, central or small-scale, natural gas | Cutoff, U – ROW" was used to convert the energy data into the impact categories. This would ensure that embodied and operational energy can be compared in the same categories. With the OpenLCA software, different LCA impact categories can be assessed. The IMPACT 2002+ method was chosen, which is a combination of IMPACTS 2002, Eco-Indicator 99, CML, IPCC and Cumulative Energy Demand [52]. The following impact categories have been assessed: global warming, ozone layer depletion, aquatic acidification, non-renewable energy, mineral extraction and carcinogens.

3.3. System boundaries

Figure 11 shows the LCI ~~life cycle inventory~~ of the old and new ducted gas heaters, as well as the energy savings from the upgrade. The life cycle starts with the transportation of the old appliance to the waste facility and the disposal of the material, which will be further explained in 3.4.1. The deconstruction of the old appliance was omitted, ~~.~~ as this was only done with equipment, not captured in the *Ecoinvent 3.4 cut-off database*, like ramps, tools, ladders and lighting. Additionally, the amount of tools would vary from upgrade to upgrade. Therefore, a distinct statement about the equipment used per upgrade could not be made. The end of lifecycle stage of the old appliance is followed by the manufacturing of the new appliance. The raw materials used in a ducted gas heater have been considered, as well as the required energy for manufacturing and transportation and are further explained in 3.4.2. For the construction stage, only transport has been considered and is further explained in 3.4.3. The installation of the new ducted gas heating system has not been further assessed due to the same reasons provided for the omission of the deconstruction phase (for the old system) above. The operational energy savings are based on data from both one year prior and after the ducted gas heating upgrade and were separately assessed. All details can be found in 3.4.4. Where possible, country specific data of the *Ecoinvent 3.4 cut-off* database were used. When this wasn't possible, global data of the *Ecoinvent 3.4 cut-off* database were used.

Figure 1~~1~~: Life cycle inventory of the old and new ducted gas heater



3.4. Data quality and sources

In terms of the data collection approach, primary and secondary data have been used. Furthermore, installation companies, manufacturers and recyclers were consulted to gain primary data but also to make reasonable assumptions when necessary. Additionally, assumptions are based on current literature whenever possible. ~~All data used in this study are made available in open-access on Figshare at https://figshare.com/s/f2dd5031beebef09497c.~~ The~~is includes the~~ weight~~s~~ of each appliance, the operational energy used per heating upgrade and the IMPACT 2002+ ~~impacts~~ results by life cycle stage are publicly available [53]. This should help readers to retrace the results and to further enhance research on this field.

3.4.1. End of life cycle stage

The transportion of the old appliance is based on a data set of 132 energy efficiency upgrades, which were part of the Energy Efficiency Improvement Scheme in Canberra, Australia. Nonetheless, this data is not specific to a ducted gas heater installation, this also includes other upgrades like air conditioning upgrades. All heating and cooling upgrades were undertaken by the same installation company. Based on this an average distance from the installation company to the recipient of the heating upgrade was used. The installation company would drive on average 53.61km within the Australian Capital Territory (ACT). It has been assumed that the same distance is needed to reach the recycling facility. The recycling facility is close to the installation company and therefore lies on the way.

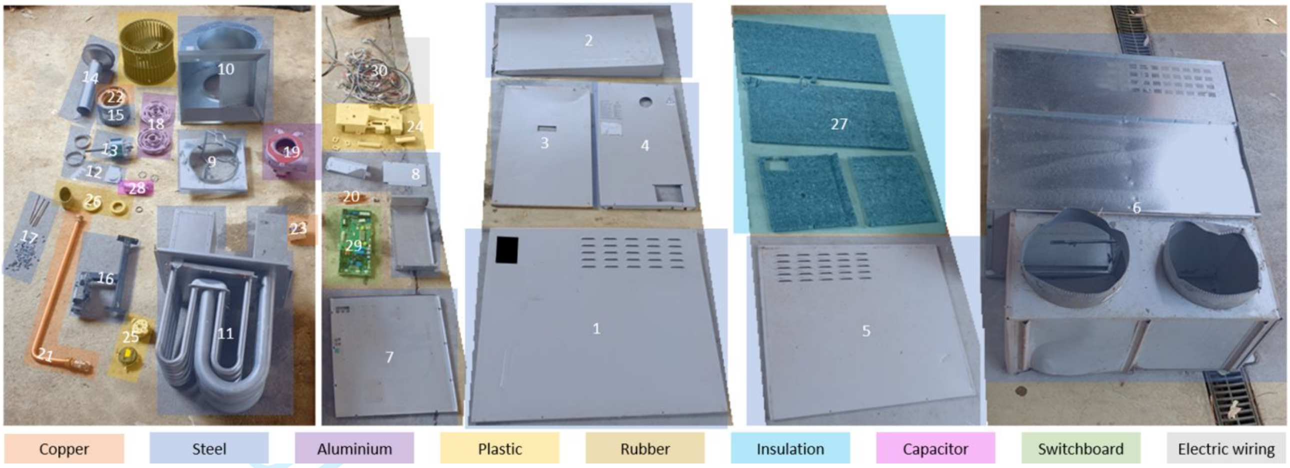
Based on interviews with recycling facilities, it ~~is presumed~~ was reported that the waste will be transported by truck from Canberra to a recycling facility in Sydney. The transportation by truck takes around 290km.

In addition, it was advised by the recycling facility that only metals would be recycled, and the remainder would go to landfill. Therefore, it has been assumed that the metals will end up as scrap metals wherefore the other materials will go to landfill. The scrap metals have been considered as outputs in OpenLCA, meaning what can be extracted from the old appliance. The further processing of the scrap metals was not considered, as there was no information available.

3.4.2. Manufacturing stage

The ducted gas heating system is a common heating solution in Australia [24]. It has one central ducted gas heater which heats the house via ducts to each room. As the length of the ducts and amount of ducts depend on the size and the amount of rooms in a house, the quantity of ducts has not been considered for this LCA. Only the ducted gas heating system was assessed. There has been limited research on ~~the~~ ducted gas heaters and consequently there was no data available on the materials of ~~the~~ ducted gas heaters. Therefore, an Australian manufactured ducted gas heater was deconstructed, and the different materials and components were quantified and analysed. A detailed view of the materials of the deconstructed ducted gas heater can be seen in Figure 22. The capacitator, switchboard and electric wiring have not been further deconstructed, as the weight of these were insignificant and are represented in the *Ecoinvent 3.4 cut-off* database, as seen in Figure 1. Copper has been listed as raw material in the *Ecoinvent 3.4 cut-off* database. For aluminium and steel cast alloy has been chosen due to its corrosion resistance, strength and hardness. [54]The type of plastic could not be determined, it has been assumed that a plastic with a high melting point was used. Therefore, the plastic materials included in the ducted gas heater were modelled with a PA 6 plastic, which melts at 220°C [55]. Furthermore, it was assumed that synthetic rubber was used instead of a natural rubber base due to its durability. For the insulation fleece, polyethylene was chosen due to its heat resistance.

Figure 2~~2~~: Material ~~compostion~~composition of deconstructed ducted gas heater



After the material had been classified, each part was weighed. The details of the measurements can be seen in Table 3. The total system weighs 69.67kg and 86.34% of the system is made of steel.

Material	No	Grams	Percentage
Steel	1	2,920	4.19%
	2	2,090	3.00%
	3	1,490	2.14%
	4	1,540	2.21%
	5	2,920	4.19%
	6	21,200	30.43%
	7	670	0.96%
	8	550	0.79%
	9	780	1.12%
	10	2,490	3.57%
	11	17,370	24.93%
	12	160	0.23%
	13	1,930	2.77%
	14	1,050	1.51%
	15	1,263	1.81%
	16	1,470	2.11%
	17	260	0.37%
Aluminium	18	390	0.56%
	19	1,690	2.43%
Copper	20	120	0.17%
	21	590	0.85%
	22	2,527	3.63%
	23	960	1.38%
Plastic	24	260	0.37%
	25	150	0.22%
	26	1,180	1.69%
Rubber	27	150	0.22%
Insulation	28	130	0.19%
Capacitor	29	160	0.23%
Switchboard	30	590	0.85%
Electric wiring	31	620	0.89%
Total		**69,670**	**100%**

Table 3: Material weight of ducted gas heater

The ducted gas heating system was used a~~s~~ reference for this research paper~~ducted gas heater~~. The shares of the material were multiplied ~~with~~ by~~the~~ 61 assessed ducted gas heating upgrades. Data from ~~of~~ the ~~old and~~ new systems were~~are~~ based on primary sources and therefore the weight of each appliance was determined based on installation manuals of the manufacturer. The model and brand of the old ducted gas heater was retrievable and the weight of 61 old ducted gas heaters could be determined based on the manufacturer’s installation manuals. The material share was then ~~counted~~ factored into~~towards~~ the weight of the old and new ducted gas heating systems. The exact weight was documented in is publicly available~~can be seen under https://figshare.com/s/f2dd5031beebef09497c.~~ [53].

As the deconstructed ducted gas heating system was Australian made, it has been assumed that the raw materials would come from Asia and would be transported to Australia by ship. The transportation journey by ship from Asia to Australia is estimated to be 10,850km. Furthermore, it is assumed that the raw materials are delivered from Melbourne harbour to the manufacturer by truck within a distance of 40km.

The manufacturing process takes place in Australia. Therefore, the Australian electricity production mix for Australia of the *Ecoinvent 3.4 cut-off database* was used. Nonetheless, primary data on the energy use of manufacturing ducted gas heating systems could not be found. A conservative approach was therefore chosen and it was estimated that 20 MJ/kg are needed to produce an appliance [56].

3.4.3. Construction stage

As for the deconstruction of the old ducted gas heater, the installation of the new ducted gas heater ~~is~~ was done with minimal equipment not captured in the *Ecoinvent 3.4 cut-off* database like ramps, tools, ladders and lighting~~. It uses a ramp, tools, ladder and lighting,~~ which ~~are~~ were excluded from ~~the present~~ the LCA. The deconstruction was consequently not considered.

For the transportation it was assumed that the installation company received the appliance from the manufacturer in bulk per truck. The manufacturer is reportedly based in Melbourne. It is 705km from the manufacturing ~~side~~ location to the installation company. Afterwards the appliance is transported to the recipient of the ducted gas heating upgrade by van, as advised by the installation company. As mentioned in “2.3.1 End of Life stage” the distance driven by van was calculated based on a data set of 132 energy efficiency upgrades. The van drives an average distance of 53.61km.

3.4.4. Use stage

Only B6 was considered as part of the use stage. The operational energy consumption is based on primary data. The data set included the gas consumption of 61 properties which received a ducted gas heating upgrade. This data includes the whole gas usage of the building and therefore could include other appliances like gas hot water systems or gas cook tops. Therefore, one year of gas consumption after the ducted gas heating upgrade was subtracted from one year of the gas consumption prior the ducted gas heating upgrade. This shows if there have been any increases or decreases in the gas usage which can be related to the ducted gas heating upgrade. While only considering the energy savings of the ducted gas heating upgrade, other gas based~~-using~~ appliances can be excluded. A range of a ~~One~~ year prior and after the ducted gas heating upgrade was chosen as it can be estimated that during this time period no further big investments, which would impact the gas usage of the building, were made. The primary data of one year prior and after the ducted gas heating upgrade have then been used as a reference value and multiplied by 20, as the life time of a ducted gas heater is 20 years [57]. Energy data which showed discrepancies have not been excluded from this research.

The operational energy savings of the 61 ducted gas heating upgrades are publicly available [53]~~. can be seen under https://figshare.com/s/f2dd5031beebef09497c.~~

To assess the global warming, ozone layer depletion, aquatic acidification, non-renewable energy, mineral extraction and carcinogens impact categories, the energy savings were fed into *OpenLCA*. The *Ecoinvent 3,4 cut-off* “natural gas” dataset was used.

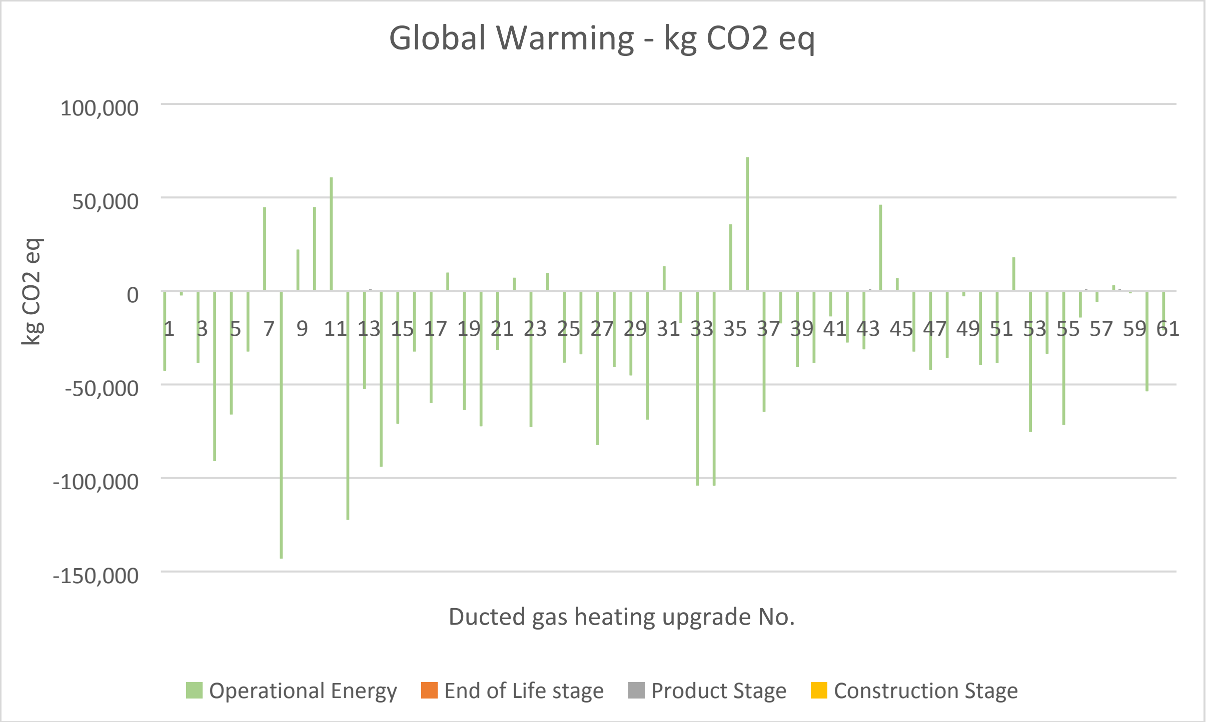
4. LCA Results reference ducted gas heating system

In summary, 61 ~~The~~ ducted gas heating upgrades were assessed on the global warming, ozone layer depletion, aquatic acidification, non-renewable energy and mineral extraction impact categories. All 61 ducted gas heating upgrades were assessed based on the weight of the old and new appliances. To extract primary data, a ducted gas heater was deconstructed, and the materials were quantified and measured. This information was used as a reference to extrapolate approximate material values in all 61 ducted gas heating upgrades based on their weight. ~~The materials of the reference ducted gas heater were used to determine the share of materials.~~ The presented results show the impact by stage and operation energy savings for each ducted gas heating upgrade. The detailed values of each impact category are publicly available [53]~~can be seen under https://figshare.com/s/f2dd5031beebef09497c~~.

4.1. Global warming

Figure 33 shows the global warming impacts by stage and the savings which were generated due to the ducted gas heating upgrade. The impacts contributed from the end of life, product and construction stages are minor in comparison to the savings generated with the ducted gas heating upgrade.

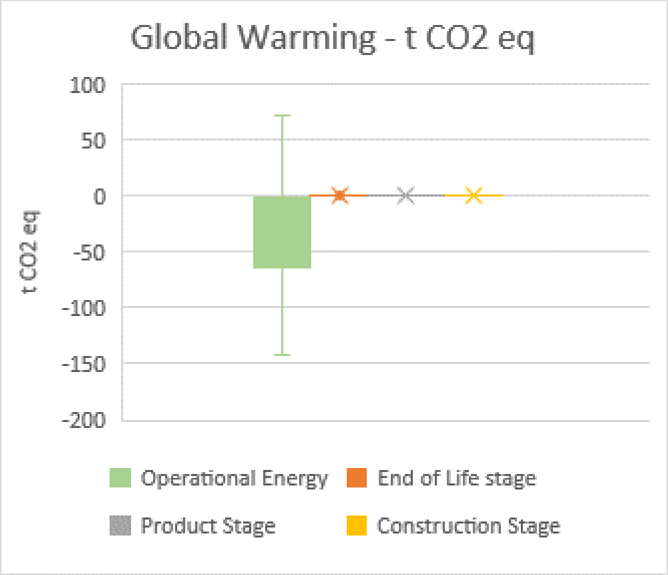
Figure 3~~3~~: Global warming impacts and savings



In total the end of life stage of all 61 ducted gas heaters upgrades requires ~~a~~ 507~~6.86~~ kg CO_2 eq., the product stage of all 61 ducted gas heaters upgrades requires 40,358~~7.76 86~~ kg CO_2 eq. and the construction stage requires 788.90 kg CO_2 eq. In total, the end of life stage of the 61 old appliances and the production and construction of the 61 new appliances account for 41,654~~3.52~~ kg CO_2 eq. On the other hand, the operational energy savings of natural gas account for -1,926,679~~.01~~ kg CO_2 eq.

The details of the split of each stage can be seen in Figure 4. Therefore, 1,885,025~~.49~~ kg CO_2 eq. were saved due to the 61 ducted gas heating upgrades. 14 ducted gas heating upgrades did not generate any operational energy savings as the gas consumption increased after the ducted gas heating upgrade. These accounted for 391,829~~.28~~ kg CO_2 eq. Nonetheless, in total the operational energy savings of all 61 ducted gas heating upgrades was higher than the increased usage. A net ~~In~~ total of 2,318,508~~.29~~ kg CO_2 eq. were saved.

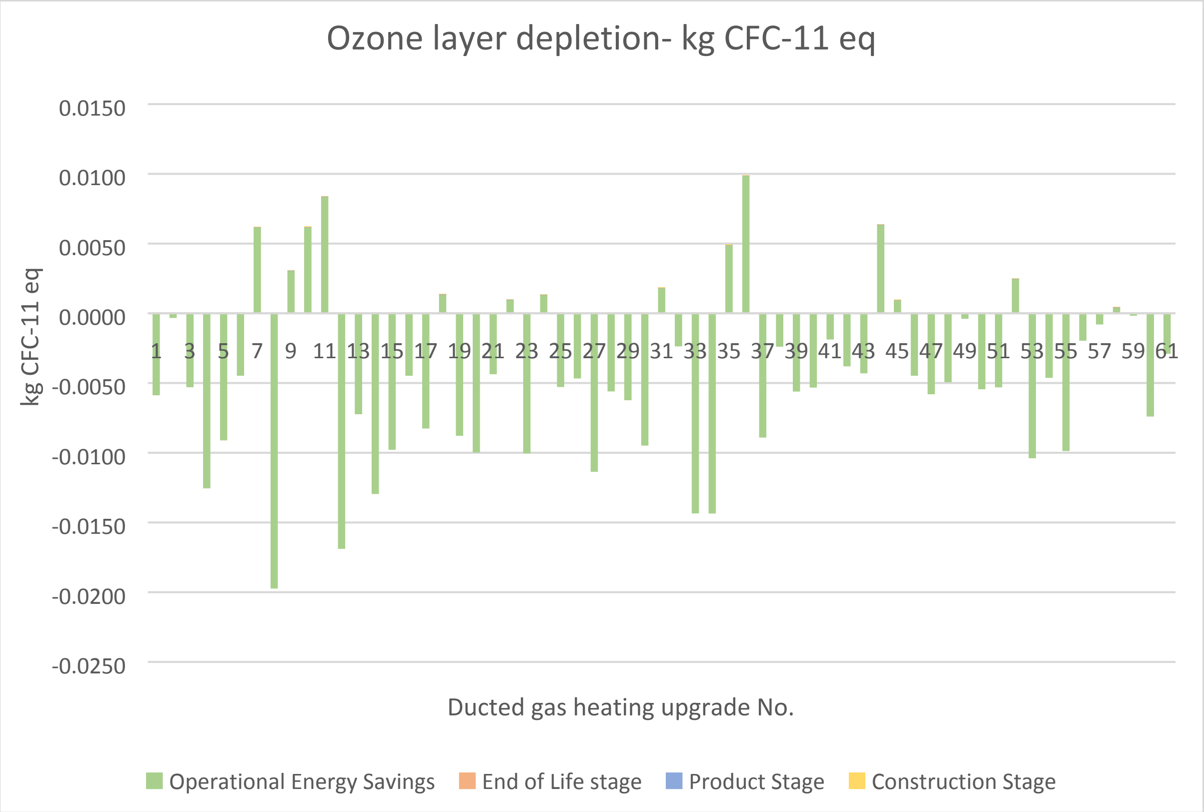
Figure 4: Global warming impacts and savings (Box and Whisker chart)



4.2. Ozone layer depletion

The ozone layer depletion in the old appliance's end of life cycle stage and in the new appliance's construction and product~~ion~~ stage is rather low in comparison to the kg CFC-11 eq. savings generated through the operational energy savings, as seen in Figure 54. Nonetheless, is does the construction stage generate the highest kg CFC-11 eq. of all the stages with 0.009645 kg CFC-11 eq. for all 61 ducted gas heating upgrades. This is due to the long-haul transportation by truck. In total 705km are required. The construction required 40km of transport by truck and the end of life requires 290km of transport by truck. In total 0.011823 kg CFC-11 eq. are generated with the disposal of the old appliance and the production and construction of the new appliance. There have been 14 households which increased their gas usage and consequently impacted the depletion of the ozone layer. Nonetheless, the operational energy saved 0.265743 kg CFC-11 eq. Therefore, a total of 0.253919 kg CFC-11 eq. can be saved when replacing an inefficient ducted gas heater with a more efficient ducted gas heater.

Figure 54: Ozone layer depletion impacts and savings

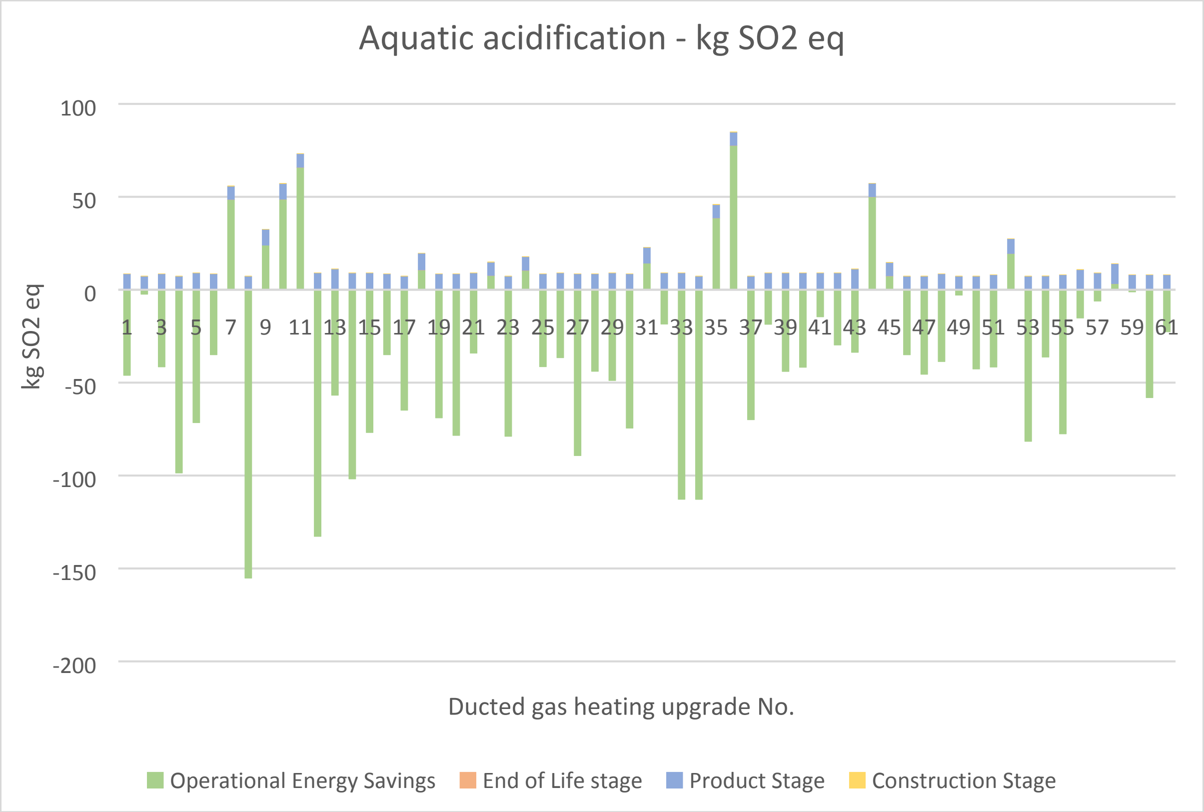


4.3. Aquatic acidification

Aquatic acidification shows the impacts of acidification to the aquatic by ducted gas heating upgrades. The operational energy savings ~~set~~ offset the impacts generated by the disposal of the old appliance and the production and construction of the new appliance. The production stage contributes the most to the aquatic acidification with 507.20 kg SO2 eq. in total for all ducted gas heating upgrades. The construction makes up for 3.99 kg SO2 eq. and the end of life stage for contributes 3.00 kg SO2 eq. This is due to the blasting and the copper production which impacts the aquatic acidification the most.

Figure 65 shows the impacts of acidification to the aquatic by ducted gas heating upgrades. The operational energy savings ~~set~~ offset the impacts generated by the disposal of the old appliance and the production and construction of the new appliance. The product~~ion~~ stage contributes the most to the aquatic acidification with 507.20 kg SO2 eq. in total for all ducted gas heating upgrades. The construction makes up for 3.99 kg SO2 eq. and the end of life stage ~~for~~ contributes 3.00 kg SO2 eq. This is due to the blasting and the copper production which impacts the aquatic acidification the most.

Figure 6~~5~~: Aquatic acidification impacts and savings

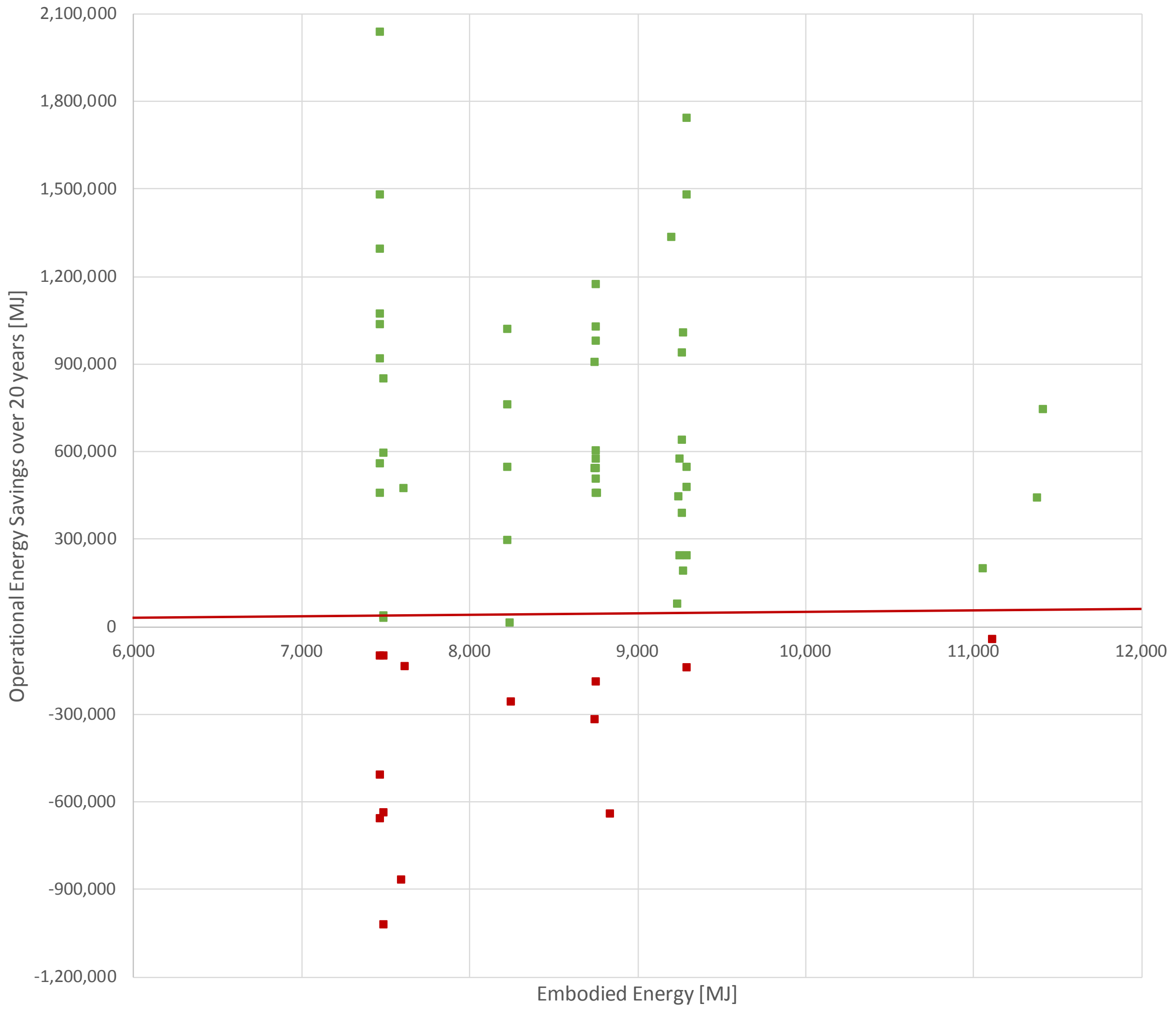


4.4. Non-renewable energy

As mentioned above the operational energy savings were based on primary data over one year. This has been multiplied by the lifetime of the appliance which is 20 years. The operational energy savings were ~~set~~ equal with the impact of non-renewable energy which is measured in MJ. Figure 76 shows that only a minority of heating upgrades do not offset the embodied energy savings with its operational energy savings. 14 households increased their gas usage wherefore 47 households reduced their gas usage. The increased gas usage makes up for 5,587,409 MJ. The gas savings make up for 33,061,473 MJ. Even though there are 14 households which overall increased their gas consumption over the lifetime of 20 years, 27,474,064 MJ can be saved for all upgrades.

The increased gas usage may be due to ~~an~~ individual households with ~~that had a~~ broken ducted gas heating systems which previously ~~wasn't~~weren't working and were replaced with plug in electric heaters. This would then cause a spike in the electricity consumption but a reduction in the gas consumption. Therefore, with a ducted gas heating upgrade the gas use of the household would increase.

Figure 76: Embodied Energy in relation to the Operational Energy Savings



The 14 ducted gas heating upgrades have been further assessed on ~~its~~ their energy consumption. In ~~the~~ Table 4, it is shown ~~can be seen~~ that all properties which received a ducted gas heating upgrade and had~~s~~ an increase in their gas consumption reduced their electricity consumption after the ducted gas heating upgrade.

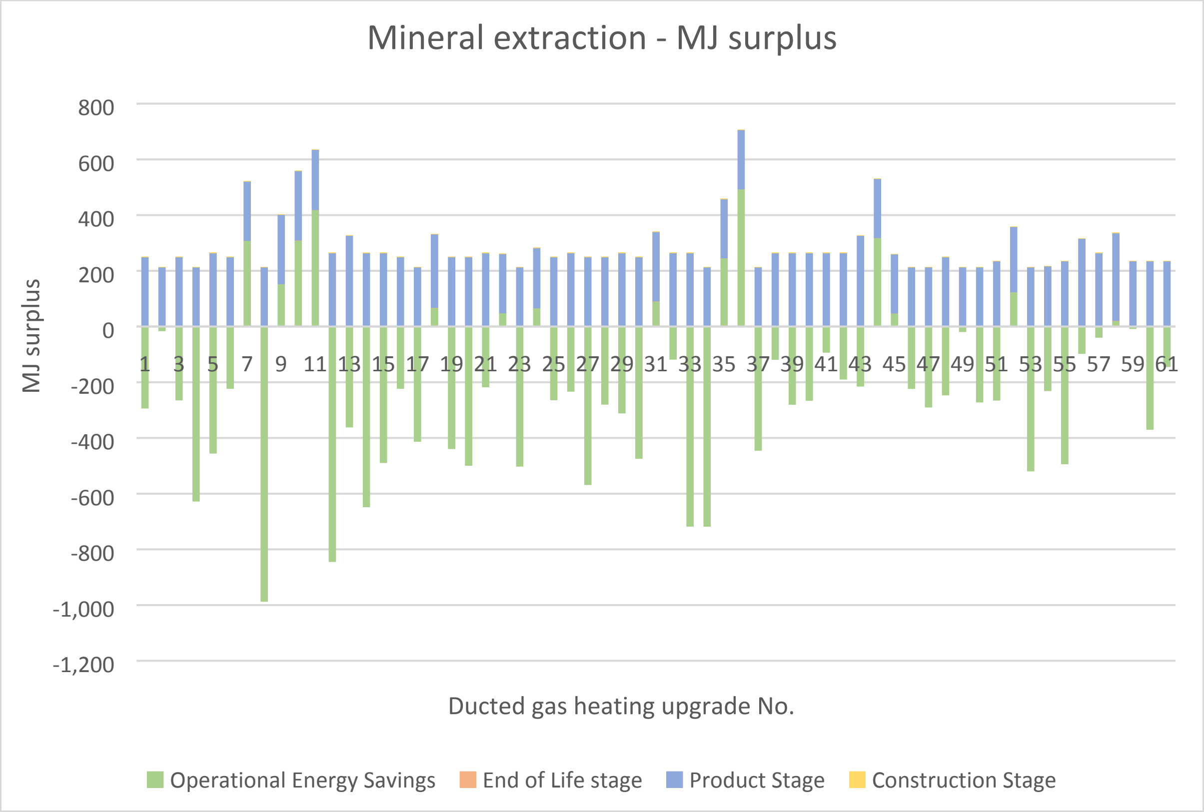
Table 4: Energy savings electricity and gas

	Electricity Consumption prior upgrade [MJ]	Electricity Consumption after upgrade [MJ]	Electricity savings [MJ]	Gas Consumption prior upgrade [MJ]	Gas Consumption after upgrade [MJ]	Gas savings [MJ]
DGH7506	27001.23084	5469.6905	-21531.5403	45251.86	77084.59	31832.7261
DGH3621	17016.28992	4849.642	-12166.6479	74555.41	90270.29	15714.8835
DGH5868	33582.32532	9854.2614	-23728.0639	83945.38	115847.5	31902.1053
DGH5972	88471.10808	22248.8835	-66222.2246	151451.8	194650.9	43199.1721
DGH6655	83853.02844	22491.3717	-61361.6567	83002.24	89938.67	6936.4265
DGH2064	34157.06424	9758.2468	-24398.8174	114623	119601.5	4978.5213
DGH5528	92921.09256	24835.0306	-68086.062	69464.74	76263.94	6799.2056
DGH5946	17049.99852	5961.8048	-11088.1937	45365.79	54703.34	9337.5503
DGH7818	87952.07808	18954.762	-68997.3161	34220.31	59530.05	25309.7407
DGH1764	57526.11324	10187.5045	-47338.6087	24836.89	75769.47	50932.5778
DGH7591	20389.01472	8126.7066	-12262.3081	13069.7	45868.07	32798.3738
DGH3954	33295.05756	8553.7378	-24741.3198	79392.38	84224.64	4832.2583
DGH.303	36795.2742	12960.1597	-23835.1145	261066.4	273790.3	12723.8895
DGH3087	27792.56268	7076.6505	-20715.9122	50965.98	53038.98	2072.9966

4.5. Mineral extraction

The mineral extraction is not offset by the operational energy savings generated from the ducted gas heating upgrade. The operational energy savings contribute in total to 13,301.45 MJ savings, the embodied energy still requires a total of 14,930.09 MJ of mineral extraction. In total 14,863.48 MJ are used for the production of all 61 ducted gas heaters. This accounts for the highest share. The construction requires 33.55 MJ and the disposal and transport of the old appliance requires 33.06 MJ. The copper mining has the highest impact on the mineral extraction followed by the ferronickel production.

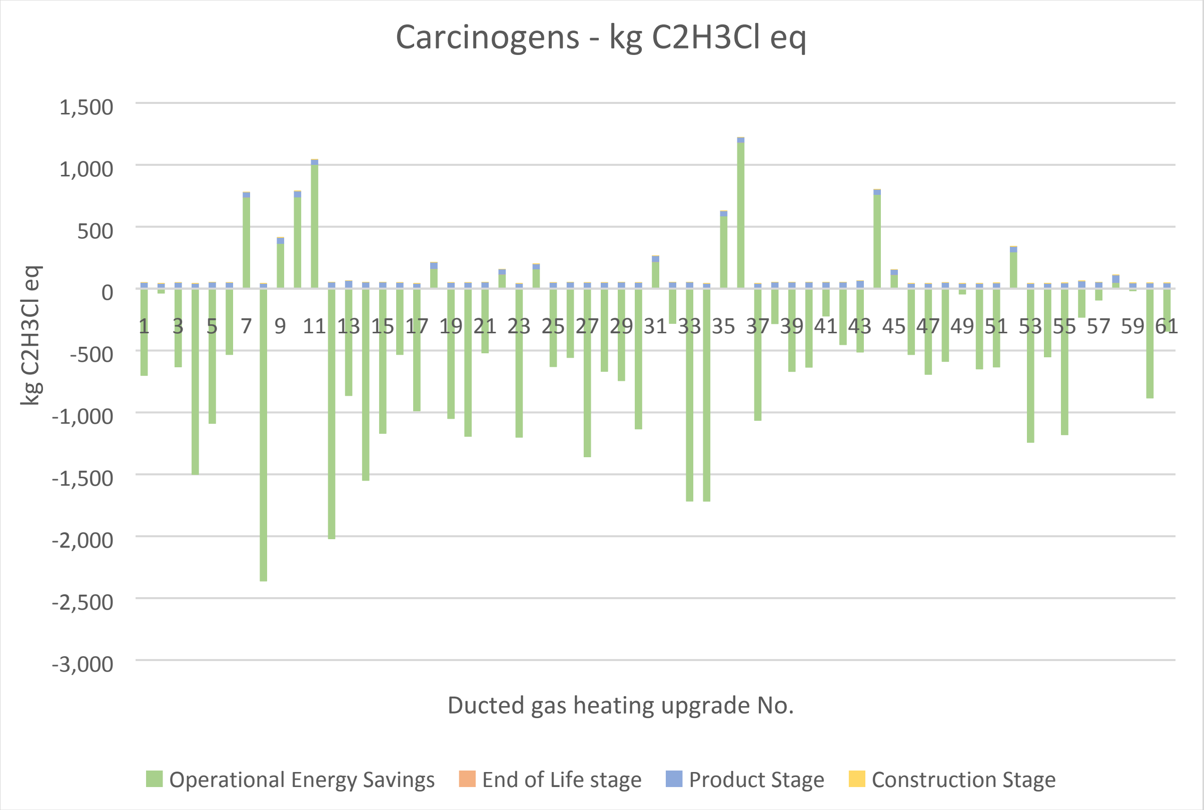
Figure 8~~7~~: Mineral extraction impacts and savings



4.6. Carcinogens

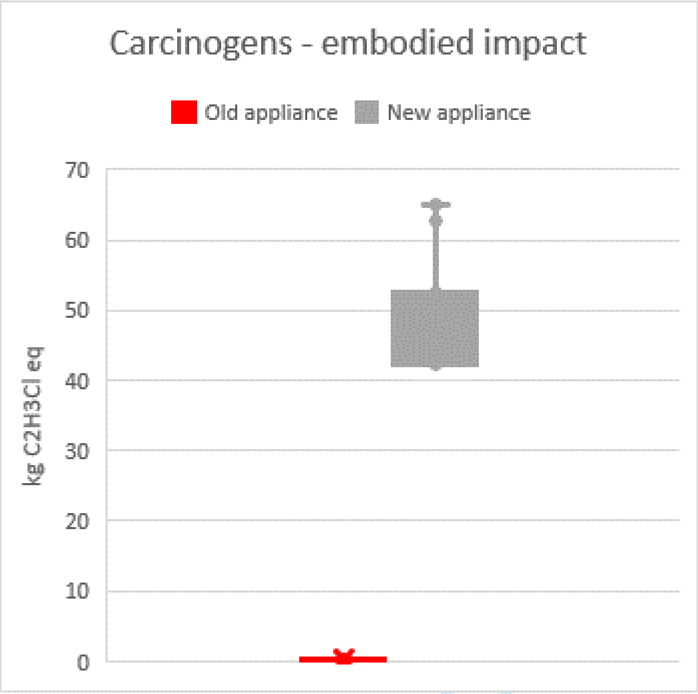
As seen in Figure 98, the carcinogens impact is heavily offset by the operational energy savings of the ducted gas heater. While the disposal of the old appliance and the production and construction of the new appliance require 2,969.44 kg C2H3Cl eq. the operational energy savings total 28,870.73 kg C2H3Cl eq. The savings make up nearly 10 times as much kg C2H3Cl eq. as was generated.

Figure 98: Carcinogens impacts and savings



When isolating the operational energy savings from the embodied energy of the old and new appliances it can clearly be seen in Figure 10 that the carcinogens impacts are significantly higher for the new appliances. While carcinogens of the old appliances are predominately impacted by hydrocarbons, which are admitted to the air due to the transportation, the new appliances are predominately impacted on arsenic and hydrocarbons emissions to air. The arsenic is mainly generated from the wiring board production while the hydrocarbon is mostly generated from steel production.

Figure 10: Carcinogens- embodied impact of old and savings



4.7. Average results

The above impact categories represent the impacts by ducted gas heating upgrades. The average impacts by category can be seen in Table 5. The average operational energy savings offset the embodied energy in the categories: global warming, ozone depletion, aquatic acidification, non-renewable energy and mineral extraction. ~~Only for the impact category, m~~Mineral extraction is the only impact category where the operational energy savings cannot offset the embodied energy. The mineral extraction of the embodied energy is 1,628.64 MJ higher than the operational energy ~~can offset~~savings.

	Operational Energy stage	End of Life stage	Product stage	Construction stage
Global warming - kg CO_2 eq	-1,926,679.01	506.86	40,357.76	788.90
Ozone layer depletion - kg CFC-11 eq	-0.004356	0.000002	0.000034	0.000158
Aquatic acidification - kg SO2 eq	-2,092.11	3.00	507.20	3.99
Non-renewable energy - MJ primary	-450,394.49	160.93	8,195.36	14,616.33
Mineral extraction - MJ surplus	-13,301.45	33.06	14,863.48	33.55
Carcinogens - kg C2H3Cl eq	-31,840.17	11.88	2,944.79	12.77

Table 5: The average values of the impact categories by stage

~~4.8. Summary~~

~~In summary, 61 ducted gas heating upgrades were assessed on their environmental impact (global warming, ozone layer depletion, aquatic acidification, non-renewable energy, mineral extraction and carcinogens) and on the operational energy savings generated through the ducted gas heating upgrade. An old ducted gas heater was replaced with a new ducted gas heater. All ducted gas heaters were determined on their weight. To extract primary data, a ducted gas heater was~~

~~deconstructed, and the materials were quantified and measured. This information was used as a reference to extrapolate approximate material values in all 61 ducted gas heating upgrades. The disposal and transport of the old appliance was further assessed via an LCA as well as the raw material supply, transport for the production, the manufacturing and the transport for the construction.~~

~~The assessment of the impact categories for all 61 ducted gas heating upgrades show that the overall operational energy savings offset the embodied energy, only the mineral extraction cannot be offset with the operational energy savings. Especially the impacts on global warming are reduced significantly when upgrading to a more efficient ducted gas heating system.~~

~~Regarding all ducted gas heating upgrades for 23% the individual situation after the energy efficient upgrade was worsening the energy balance albeit for the whole 61 upgrades the overall energy savings outweigh the embodied energy. As 61 ducted gas heating upgrades have been considered it can be said that various individual heating behaviours are included and that there is a strong tendency in reducing the overall gas usage after upgrading to a more efficient ducted gas heater. It also was found that the households which increased their gas usage after the ducted gas heating upgrade decreased their electricity usage. This can be due to a broken ducted gas heating system which has not been used prior to the upgrade while electric portable heating systems have been used instead.~~

5. Discussion

Following common energy efficiency upgrades it can be said that gas heating is not the most sustainable choice of heating. In 2019 a dwelling in the ACT accounted for 165,100 kg CO_2 over its lifetime [58]. In comparison the annual CO_2 eq. savings of the ducted gas heating upgrade account for 94,251 kg CO_2 eq. While heating makes up for around 20% to 50% of a buildings energy consumption [23] the upgrade to a more efficient ducted gas heating system will reduce carbon emissions despite its embodied energy. Despite previous literature on this topic, this research paper uses real energy consumption data of 61 properties which received a ducted gas heating upgrade. Therefore, different behavioural heating preferences and energy uses are included. This strongly shows that real data of the operational energy usage are important to determine whether the environmental impacts of embodied energy can be offset, as there have been 14 properties which increased their gas usage after the upgrade. Considering 61 heating upgrades show that a large spectrum of appliances is necessary to exclude any variances.

Nonetheless, ~~is~~ it is important to know the life cycle impact of a ducted gas heater to make a conscious decision for a more sustainable heating, and evidently ~~eventually~~ cooling, alternative. While considering the environmental impact of a ducted gas heater over its lifetime it can be compared to other building appliances. As this study showed the operational energy savings offset the embodied impacts, except the impact category of~~ies ozone layer depletion (kg CFC-11 eq) and~~ mineral extraction (MJ surplus). Nonetheless, ~~will~~ the non-renewable energy savings generated through the upgrade also offset the impacts of the mineral extraction. ~~I~~On average 1,885,025.49 MJ of non-renewable energy can be saved while upgrading to a more efficient ducted gas heating upgrade. The surplus of 1,628.64 MJ of mineral extraction makes only up for 0.1%. Therefore, the environmental benefits outweigh the impacts generated by the production of a new ducted gas heater.

~~Nonetheless is this study limited to the Australian market. As in Australia the typical type of heating is reverse-cycle heating, followed by gas heating, this might not apply to other countries. Also, the study has considered an Australian manufactured ducted gas heater, which reduces the impact on transportation emissions. While having tried to use predominately primary data, still assumptions had to be made which might impact the results of this study. It would be recommended to replace the assumptions with real data when these become available and to also assess systems which are manufactures outside of Australia.~~

6. Conclusion

A ducted gas heater has a significant impact on our environment over its lifetime. While there is currently limited research on building appliances this research paper clearly stated that there is a need for further research on building appliances and knowing their environmental impact. Assessing appliances via an LCA establishes a framework where appliances can be systematically compared helps to make them comparable and will help decision makers ~~to~~ make an informed ~~conscious~~ choice for ~~a~~ more environmentally friendly alternatives.

This study assessed the environmental impact of an Australian ducted gas heater. While only limited research is available, a ducted gas heater was deconstructed and assessed on its material and quantities. Furthermore, installation companies, manufactures and recyclers were contacted to gain primary data but also to make reasonable assumptions when necessary. After the data collection ~~part~~component, the system was then assessed via an LCA. The results clearly show that the operational energy savings offset the impacts generated with the end of life treatment of the old appliance as well as the product and construction stage of the new appliance (global warming, ozone layer depletion, aquatic acidification, non-renewable energy, carcinogens). ~~has the highest impact for nearly all assessed categories, including Abiotic resource depletion (fossil fuels), Acidification, Climate change (biogenic, fossil and land use) and Land use.~~ This is due to the high use of natural gas during its lifetime. In average 1,885,025.49kg CO_2 eq., 1,577.92 kg SO2 eq, 425,793.23 MJ and 28,870.73 kg C2H3Cl eq can be saved. Only the mineral extraction cannot be offset by the operational energy savings. Conversely, 0.0042 kg CFC-11 eq. get released to the atmosphere.

The results show that the embodied energy only makes up for a small portion. The highest impact ~~lies~~ remains in the actual operational energy. 23% of the households receiving a ducted gas heating upgrade increased their operational energy use after the upgrade. This can be due to the rebound effect and therefore a heating upgrade should also improve ~~include~~ the educational awareness~~level~~ on how to avoid the~~an~~ inefficient usage of ~~the~~ a system. Also, it can be due to a broken ducted gas heating system which has not been used prior to the upgrade while electric portable heating systems have been used instead. Nonetheless, ~~did~~ the overall operational energy savings outweigh the increased energy use by 27,474 GJ over the lifetime of the appliance (20 years). Therefore, it can be assumed when using a more efficient gas heater with a lower gas use that this would significantly reduce the environmental impacts. Moreover, a ducted gas heating system can also be replaced with a ducted reverse-cycle air conditioner when the cavity space allows for the normally larger ducts to have enough space. It would also be ~~from~~ of interest to compare~~see what~~ the environmental impact ~~it would have to~~of replacing~~e~~ a ducted gas heater with a more efficient heating and cooling system to the ~~and which~~ impact of~~s it would have to~~ changing~~e~~ the source of heating from natural gas to electricity.

Nonetheless, is this study limited is to the Australian market and is influenced by economic, social, political, legal and environmental pressures unique to Australia. As in Australia, the typical type of heating is reverse-cycle heating, followed by gas heating, this might not apply to other countries. Also, the study has considered an Australian manufactured ducted gas heater, which reduces the impact on transportation emissions. While having tried to use predominately primary data, still assumptions still had to be made which might ~~impact~~affect the results of this study. It would be recommended to replace the assumptions with real data when these become available and to also assess ~~systems~~appliances which are manufactured~~s~~ outside of Australia.

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Life cycle assessment of 61 ducted gas heating upgrades in Australia

Abstract

Operational energy use in buildings accounts for 28% of global energy demand. One method to reduce operational energy is upgrading old appliances to more efficient ones. In Australia, the most common residential heating type is reverse-cycle heating, followed by gas heating.

This research paper aims to determine the energy balance resulting from a gas heating upgrade through a life cycle assessment (LCA). Extensive primary data was collected for operational energy performance of 61 ducted gas heating upgrades. To address the scarcity of data on material composition, one ducted gas heater was deconstructed and assessed in terms of material composition (types and weights). The comparison between embodied energy and operational energy savings allows us to establish whether operational energy savings offset the embodied energy incurred with the upgrade.

The end of life stage of the old appliance, as well as the production, construction and use stage of the new appliance were assessed. Results show that operational energy savings offset the following impact categories: global warming, ozone layer depletion, aquatic acidification, non-renewable energy, and carcinogens. Only the mineral extraction is not offset by the operational energy savings. Results clearly demonstrate that operational energy savings outweigh the embodied energy and therefore contribute positively to the environment.

This study is the first to focus on the LCA of building services through extensive primary data collection and a focus on a high number of appliances. This supports ongoing energy efficient upgrades in Australia and pave the way for further, similar studies to confirm or disprove these findings in other parts of the world.

Keywords: Building services, Ducted gas heater, Gas heating, Life cycle Assessment, Embodied energy, operational energy, primary data

1. Introduction

Buildings account for more than 40% of global energy demand and nearly one third of global greenhouse gas (GHG) emissions [1-3], therefore it is important to address the significant environmental impacts of buildings and construction by evaluating buildings and their components through a whole-life lens [4].
To lower carbon emissions produced by existing buildings, energy efficient refurbishment is one solution, predominantly when considering that buildings have long lifespans and that often the structure is sound enough to warrant extending the building's lifespan [5-7]. In this regard, improving energy efficiency of existing buildings can strengthen the energy security worldwide and lower carbon emissions. The life cycle of refurbishment measures is principally used to assess both the materials to be added to existing building and the energy consumption patterns of users [8].

When considering the entire life of a building, operational energy is often considered the most relevant part of the building's life cycle [9-12]. The operational energy is used to heat, cool, ventilate and power appliances within the building. Embodied energy is the energy required through processes of producing buildings materials [13] and when combined with operational energy, can be assessed via a whole-of-life approach. The Australian Capital Territory (ACT) Government has capitalized on the potential of reducing energy consumption in homes and businesses and introduced in 2013 the Energy Efficiency Improvement Scheme (EEIS) [14]. The scheme puts an energy saving obligation on retailers which requires that large retailers undertake approved energy saving initiatives while smaller retailers have the option to deliver initiatives or pay a contribution to fund those initiatives [15]. The energy saving activities under the EEIS include, inter alia, upgrading old ducted gas heaters to more efficient appliances. This energy saving activity seems to have a great energy saving potential, as in Australia, the most common residential heating type is reverse-cycle heating, followed by gas heating [16]. Furthermore, heating makes up for around 20% to 50% of a building's energy consumption [17]. The question arises what potential benefits can result from a heating upgrade? Therefore, the research paper aims to answer the following questions:

- How much operational energy can be saved through a ducted gas heating upgrade, and can the overall environmental footprint be lowered?
- Do the resulting operational energy savings from replacing ducted gas heaters offset the embodied energy of the new appliance?

To answer these questions, a reference ducted gas heater has been deconstructed and assessed for its materials. A dataset of old and new appliances has then been assessed and compared over their life cycles. The operational energy savings have been taken into account as well, to estimate if the savings offset the environmental impacts of the upgrade. This paper is aiming to help decision makers make a conscious and informed decision on the implementation of ducted gas heating upgrades while considering the whole life cycle impacts. It furthermore attempts to identify further potential benefits of a heating upgrade.

The next section reviews literature of LCA studies assessing building heating and cooling appliances. Section 3 presents the research design and methodology, while Section 4 presents the results of the LCA which are discussion in Section 5. Section 6 concludes the research paper.

2. Literature Review

To ensure no duplications and highlight the necessity of this study, a literature review was conducted. Due to fast changes in technology the current literature of the last ten years was systemically reviewed. The systematic approach was used to ensure studies were selected objectively without omitting relevant literature and to ignore irrelevant publications.

Therefore, Web of Knowledge was used to identify studies with the following key words:

- energy efficiency;
- residential building;
- life cycle assessment (LCA);
- retrofit;
- refurbishment;
- heating and cooling;
- building service;
- building appliances;
- heating appliance; and
- HVAC system.

A combination of several key words was used to find literature regarding LCAs on residential retrofits, energy efficiency upgrades and LCAs on heating and cooling upgrades. The results showed that there is only limited research available to considering the life cycle of explicitly heating and cooling upgrades, meaning replacing an old heating and cooling appliance with a new one.

2.1. Life Cycle Assessment

An LCA is the assessment of environmental impacts of a product, process or service over its whole life (from cradle to grave) and became a commonly used tool over the years [3]. Significantly, LCA offers the possibility to compare different products and simply pinpoint opportunities of improvement. Also, the consideration of all stages of a product or service and the exposing of data make LCA a commonly used methodology [18].

In accordance with ISO 14040, an LCA consists of defining the goal and scope, creating the life cycle inventory, assessing the impact and finally interpreting the results [19]. The assessment commonly includes the entire life cycle from raw material extraction, manufacturing, construction, operation and maintenance to the end-of-life (demolition, disposal, reuse and recycling) [4, 20]. Common impact categories assessed during the life cycle of a product are global warming potential (GWP), depletion of minerals and fossil fuels, photochemical oxidation (smog), human toxicity, ozone depletion, eutrophication, water use, land use, acidification and ecotoxicity [4].

2.2. Life cycle of building appliances

The residential sector offers a significant potential for energy savings [21] and there is currently plenty of literature available which separately examines LCAs, residential building retrofits and heating systems. However, when looking at these three research fields combined, relevant literature is limited. Hence, strategies and policy efforts should focus on encouraging architects, developers, builders and household residents to seek sustainable ways of creating comfortable homes whilst minimising environmental impacts.

Most of the literature assessed considers the building envelope as a retrofitting strategy whereby heating systems are only considered from an operational point of view and rarely as part of a whole

LCA. The consequences of such shortcomings are well evidenced by the recent landmark publication from the UK's Chartered Institute of Building Services Engineers (CIBSE), which represents a world-first methodology for the life cycle assessment of building services [22]. Certain energy efficiency upgrades like building insulation may reduce operational energy but significantly increase a building's embodied energy [23]. When investing in energy-efficient and low-carbon intensity heating and cooling technologies, the final energy demand in buildings could be reduced by 25% [3]. In a scenario where a building has greater energy efficiency appliances, the largest environmental impact might reside in the production phase of the product [24].

Hence, it is important to look at the life cycle of heating and cooling appliances. This literature review therefore focuses on the literature available which examines the complete life cycle of heating and cooling systems. The available literature is listed in

Table 1, listing each life cycle stage investigated in accordance with the BS EN 15978:201 which is a European Standard to assess the life cycle of new or refurbished buildings. Furthermore, the table list the type of heating and cooling system.
There is only limited literature available on energy efficient heating and cooling upgrades. LCAs of building services are rare, with the exception of solar heaters that have been analysed from a life cycle perspective [25, 26]. Moreover, the research is primarily limited to gas or electric heating, heat recovery and mechanical ventilation, air conditioning, heat pumps and multiple heating systems.

Authors	Country	Heating system(s)		BS EN 15978:2011 Life Cycle Stages																
		Old	New	A 1	A 2	A 3	A 4	A 5	B 1	B 2	B 3	B 4	B 5	B 6	B 7	C 1	C 2	C 3	C 4	D
[27]	Turkey	Gas boiler and coal boiler	▪ Heat pump	x	x		x	x		x				x			x		x	
[28]	Saudi Arabia		▪ Air conditioning	x	x	x	x							x					x	
[29]	Germany	Baseline Scenario	▪ Natural gas boiler ▪ Infrared system ▪ Heat pump ▪ Electric baseboards ▪ Oil boiler	x	x		x	x						x		x			x	
[30]	Italy	N.A.	▪ Gas fired heater ▪ Gas fired autonomous heater ▪ Air conditioning (office building)			x	x	x						x			x		x	x
[31]	UK	Gas boiler	▪ Ground source heat pumps (GSHP) (air, ground and water)	x	x	x	x	x		x				x			x		x	x
[32]	China	N.A.	▪ Centralized air conditioning ▪ Split air conditioning	x	x	x	x	x					x	x		x	x			
[33]	N.A.	N.A.	▪ Air conditioning	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	
[34]		N.A.	▪ Space Heating and Cooling	x		x					x	x	x	x	x	x		x	x	

Authors	Country	Heating system(s)		BS EN 15978:2011 Life Cycle Stages																
		Old	New	A 1	A 2	A 3	A 4	A 5	B 1	B 2	B 3	B 4	B 5	B 6	B 7	C 1	C 2	C 3	C 4	D
[35]	Finland	Electric heating	▪ Air-source heat pump (ASHP) ▪ Novel ground-source air heat pump	x	x	x	x							x				x	x	
[21]	Canada	Baseboard heating	▪ Gas furnace ▪ Wood pellet stove ▪ Envelope conforming to the national building code 2015 (NBC+R) ▪ Envelope conforming to the Novoclimat1 2.0 program ▪ ASHP ▪ Combined scenario with improved insulation and ASHP (Novo+ASHP) and ▪ GSHP.							x				x		x		x	x	
[36]	Sweden	Mechanic ventilation	▪ Mechanic ventilation ▪ Heat recovery ventilation	x	x	x	x	x		x	x	x	x	x		x	x	x	x	
[37]	US	N.A.	▪ Central natural gas furnace heating and	x		x	x							x					x	x

Authors	Country	Heating system(s)		BS EN 15978:2011 Life Cycle Stages																
		Old	New	A 1	A 2	A 3	A 4	A 5	B 1	B 2	B 3	B 4	B 5	B 6	B 7	C 1	C 2	C 3	C 4	D
			conventional central air-conditioning ▪ Natural gas-powered hydronic heating and conventional central air-conditioning ▪ Electric air–air heat pump for heating as well as cooling.																	
[38]	France	N.A.	▪ Electric heat pump ▪ Wood pellet condensing boiler ▪ Wood pellet micro-cogeneration unit ▪ District heating			x		x		x				x		x		x		
[39]	UK	Gas boiler	▪ Hybrid Heat pump	x	x	x	x			x				x	x		x	x	x	x
[40]	Italy	N.A.	▪ Combi boiler (air and propane) ▪ Condensing boiler (gas)	x	x	x	x							x					x	

Table 1: List of literature assessing heating and cooling appliances

2.2.1. Life cycle of heating appliance

Thiers and Peuportier [38] compare different heating systems and the thermal comfort of different building types; two attached passive houses and a renovated apartment complex. The apartment complex has a significantly higher consumption, which relates to the larger floor area. The results of the LCA show that the heat pump and micro-cogeneration system are higher for the apartment complex in most of the assessed categories, except ecotoxicity, human health and odour [38]. It is worth mentioning, that the focus of the research was not on the heating system itself but rather on the energy performance of the building. Therefore, the embodied energy of the heating systems was not assessed. Asdrubali, Baldassarri and Fthenakis [30] also predominately focus on the overall performance of the building than the heating appliances. The findings of the above research show that an energy efficiency upgrade in a detached house has a lower environmental impact then in a multi-story house. This may be the result of having one system for the detached building in comparison to several systems for the multi-complex building. Ramírez-Villegas, Eriksson and Olofsson [36] also modelled energy efficiency in combination with wall insulation. Again, the energy consumption has been modelled and does not rely on real data. These have been modelled with a building energy simulation tool (EQUA, 2013). While modelling different temperature settings, the environmental impact varies for each energy efficiency upgrade. This makes it hard to compare a change in temperature and will consequently result in an increase of electricity; causing a higher environmental impact [41]. The study's authors advise on keeping energy setpoints constant to ensure an accurate comparison.

Lin et al. [39] assessed the life cycle of a gas boiler and a hybrid heat pump via an LCA. The SimaPro 8.0 software was used to assess 14 impact categories via the Ecoinvent v3 database. The assessed stages of the two boilers are heavily based on assumptions. The energy data are based on the recommendation of the manufacturer and do not include behavioural tendencies of the users. A sensitivity analysis was conducted, the findings had shown that the global warming potential is 30% to 40% lower for the hybrid heat pump. The impacts of the gas boiler were only higher for the human toxicity, water depletion and metal depletion. However, this study heavily relied on secondary data, a larger scale of energy consumption data would be recommended to have a real representation of the operational energy usage. Vignali [40] assessed the life cycle of a conventional gas boiler and a condensing boiler in three different locations in Italy and for two types of dwellings. The inventory data for components and packaging were provided by the manufacturer and Ecoinvent was used as secondary source of data. SimaPro version 7.3.3 was used to calculate via CML2001 the life cycle impacts. The boilers were assessed on six impact categories (Acidification Potential, Eutrophication Potential, Global Warming Potential for a time horizon of 100 years, Photochemical Ozone Creation Potential, Stratospheric Ozone Depletion Potential and Cumulative Energy Demand) for both dwellings in three locations in Italy. Also, have the same stages been considered for both boilers which makes a comparison reasonable. The energy consumption is not based on primary data, but on the efficiency of the boilers in different scenarios. The findings had shown that the impacts of the condensing boiler were 30 % lower for the acidification potential, 48% for the eutrophication potential and 24% for the photochemical ozone creation potential. The impacts of the condensing boiler were also 15% lower for energy demand, global warming, and ozone depletion potential. Vignali also states, that the environmental sustainability of boilers can be improved by optimizing the energy efficiency of these systems [40].

2.2.2. Life cycle of heating and cooling appliance

Li [33] assesses the environmental impact of an air conditioner via the Ingersoll Rand's (IR) Screening LCA tool, which is not commonly used. Four impact categories (Global Warming Potential, Acidification Potential, Eutrophication Potential and Ozone Depletion Potential) have been assessed in total. The material compostion shows that both air conditioners predominately consist of carbon steel (aprox. 47%), aluminum (aprox. 10%) and ferrous (aprox. 17%). The real origin of the material information stays unclear. The energy data are based on modelling and results in 70% of the environmental impact coming from operational energy use. Therefore it would be ideal to base the energy consumption on real data. The second highest contributer to the environmental impacts is the refrigerant leakage. The raw materials which are predominately steel and aluminium have only a minor impact. [33]. The LCA section of the paper is kept relatively short and some origins of the data stay unclear. Also the research does not give detailed information on the material composition, the share can only be seen in graphs.

Asdrubali, Baldassarri and Fthenakis [30], Pedinotti-castelle et al [21] and Ramírez-Villegas, Eriksson and Olofsson [36] only consider a heating (and cooling) upgrade in combination with other energy efficient retrofits like the upgrade of the building envelope. Asdrubali, Baldassarri and Fthenakis [30] investigate the upgrade of a gas fired heating system for three different types of buildings via an LCA but most of the data is based on assumptions like the energy consumption of the building and the buildings are difficult to compare due to different sizing. It would be relevant to break the impact down per capita, as the floor area and number of occupants is different; allowing for more accurate analysis [42, 43].

2.2.3. Life cycle of heating and cooling retrofits

Hu and Zheng [32] investigate the impact of a centralized split air conditioner in a short research paper. The values represented in the research paper have no further information provided of its origin. Ramírez-Villegas, Eriksson and Olofsson [36] only consider an air conditioner for an office building wherefore the results cannot be compared [21]. The same problem can be found for heat recovery and natural ventilation systems. The only heating system which has been broadly examined in literature is the heat pump. The heat pump retrofits in this literature review predominantly were compared to gas boiler heaters. The main findings from literature all agree that the heat pump has larger environmental impacts than a gas boiler. This is primarily due to the grid electricity mix and less a result of endogenous traits of each system [30, 37]. Almutairi et al. assesses the life cycle of an air conditioner. The air conditioner is split by its material and the electricity composition of Saudi Arabia is assessed. The study clearly states that the operational energy use has the highest impact due to the high use of fossil fuels in Saudi Arabi [28].

Greening and Azapagic [31] assessed the life cycle impacts of an air, ground, surface water and groundwater source heat pump in comparison to a gas boiler for the residential building sector. While using GaBi v. 4.4, the environmental impacts (Abiotic resource depletion of elements, Abiotic resource depletion of fossil fuels, Acidification potential, Eutrophication potential, fresh water aquatic ecotoxicity potential, Global warming potential, Human toxicity potential, Marine aquatic ecotoxicity potential, Ozone layer depletion potential and Photochemical ozone creation) were assessed with the CML 2 Baseline 2001 methodology. Nevertheless, maintenance and installation has not been considered for the gas boiler wherby it was for the heat pump systems. This reduces the comparability. Data on the material, installation and infrastructure of the appliance were sourced from manufacturers, contractors and operators. The study demonstrated that ground and

water source heat pumps perform better than air source heat pumps. This is due to the lower efficiency rating of the air source heat pumps, as the main contributer is the operating energy. Even with a sufficiently decarbonised electricity grid will the life cycle impacts of the heat pump be higher. Abusoglu and Sedeeq [27] used an exergo-environmental analysis to compare the energetic, exergetic and environmental performance of a ground source heat pump with a conventional coal and gas fired heating system. Material data were sourced from the manufacturer and Ecoinvent. Only the components and corresponding weights of the appliances have been shared but the split of data from the manufacturer and Ecoinvent is not visible. The impact categories were assessed via SimaPro v.7.1 and the IMPACT 2002+ analysis was selected. The results state that the ground source heat pump has a better energetic
and exergetic efficiency than the fuel powered boilers, due to the minimum exergy destruction. Nonetheless, the environmental impact is the highest for the ground source heat pump, similar to the findings of Greening and Azapagic. Abusoglu and Sedeeq state that this is due to the use of copper and the R-134a refrigerant which needs an annual maintenance of 0.1 kg. Furthermore, the impact of the heat pump with 80% renewable electricity grid was conducted and the heat pump still had higher environmental impacts. Nonetheless, the study examined by Abusoglu and Sedeeq [27] does not consider the same scope for the heating upgrade as for the existing heater. Hence, the heat pump includes the installation and maintenance of the system, which has been excluded for the fossil fuel boiler. Also, the fossil fuel boiler system heats via radiators while the ground source heat pump heats via floor heating. This false comparison impacts the life cycle results, as more stages have been included for the upgrade which consequently have a higher impact. Only Shah,

Shah, Debella and Ries [37] consider a gas heater in combination with an air conditioner, as the heat pump also provides cooling in summer. Even when comparing the heat pump with a gas heater in combination with an air conditioner, the heat pump has higher environmental impacts which can be linked to the grid electricity mix. The environmental impacts of the heat pump have been shown to only be higher in regions with higher proportions of fossil fuels in their grid electricity mix. Therefore, the study of Shah, Debella and Ries [37] contradicts Abusoglu’s and Sedeeq’s [27] study. In comparison with an electric heater, the heat pump is a more environmental friendly option [29, 35]. In a similar vein, Mattinen et al. [35] found that due to digging and drilling for pipes of the ground source heat pump, the air source heat pump is easier to install but that the ground source heat pump is the most environmentally-friendly solution when considering the greenhouse gas emissions produced during its life cycle. All studies are based on assumptions for the operational use and show a need for real data on operational energy prior to and post a heating and cooling upgrade.

2.2.4. Summary

Examination of the literature uncovered a dearth of studies covering the embodied energy of refurbishments involving the replacement/upgrade of heating and cooling appliances [33]. This is due to the difficulty of evaluating the mechanics of the appliance and the rather low impact of carbon emissions during the manufacturing process in comparison to the carbon emissions produced during operational use [44]. The life cycle stages which have been considered by Li [33], Longo et al. [34] and Ramirez-Villegas et al. [36] whereby other authors appear to focus on distinct stages. It can be seen in

Table 1 shows that there is a focus on A1, A3, A4 and B6, whereby B7, D, B4 and B3 are more frequently disregarded. Also, most research focuses on Europe, Turkey, Saudi Arabia, the US and China. No studies focus on Australia. This literature review illustrated that there is a gap in literature available assessing the life cycle of heating and cooling retrofits and that there is in particular a gap in literature on Australia. Additionally, the identified studies compare different heating systems; leading to difficulty in comparing and verifying results. The heat pump appears the most examined system followed by the gas heater, as it can be seen in

Table 1. Additionally, most studies are based on assumptions and do not take into consideration energy consumption prior and after to the retrofit. All studies are based on energy consumption modelling. There is a need for real data to make stronger statements about the savings generated from heating and cooling upgrades and if these offset the environmental impact of the production, construction and end of life stages. Furthermore, current research is based on a small spectrum of appliances. Varying consumer behaviour can have a large impact on the operational energy. While bringing energy efficiency upgrades on scale, a more precise statement can be made if this energy efficiency upgrade is beneficial. The large amount of assumptions therefore makes it hard for decision makers to apply the theory in practice. It is recommended to use more primary data and ensure accurate findings to limit error rates. Furthermore, the current research is commonly only backed up with a small set of data, whereby especially energy consumption data would benefit from a larger set of data to eliminate energy behaviour. There is a demonstrated gap in research in LCAs of energy efficiency upgrades for heating and cooling appliances. This gap is worth exploring in future research.

3. Research design, methods and data

This section introduces the LCA methodology with its goal and scope, the methods used in the research as well as the input data used.

3.1. Goal and scope

The goal of this study was to determine if the energy savings from replacing a ducted gas heating system with a more efficient six-star energy rated ducted gas heating system will outweigh the embodied energy. The assessment was conducted in alignment with the stages of the BS EN 15978-2011 and the ISO 14040 guidelines. The European Standard outlines the calculation method to assess the environmental performance of new or refurbished buildings based on their life cycle and quantified environmental information. The scope of the study ranged from the extraction of the raw material to transport, to manufacturing and use of the new appliance to the disposal and transportion of the old appliance (see Table 2). Other stages have been excluded due to the lack of data and to avoid distorting the results based exclusively on assumptions. The Deconstruction and Construction – installation process was excluded as the deconstruction and installation of the ducted gas heating system does not require heavy machinery. Craftsmen tools were used and occasionally ramps to lift the appliance to the cavity of the ceiling. As there has been no data available for which appliance needed lifting and which exact appliances were used it has been considered that no accurate assumptions can be made to be considered. The installation company advised that the maintenance, repair, replacement, and refurbishment requests could not be recorded in sufficient detail (relevant for this research paper), as the customers had the choice of either going to the installation company or the manufacturer directly. Data from the manufacturer could not been sought. Hence, to not impact the results these stages have not been considered. The operational water use does not apply to the ducted gas heating system and has therefore not been included.

Waste processing has been further excluded, as details about the waste processing facility were not available. The scope includes consideration of global warming, ozone layer depletion, aquatic acidification, non-renewable energy, mineral extraction and carcinogens categories.

LIFE CYCLE ASSESSMENT

PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARY
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw Material Supply	Transport	Manufacturing	Transport	Construction - installation-process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction	Transport	Waste processing	Disposal	Reuse, Recovery, Recycling-potential
x	x	x	x							x			x		x	

Table 2: Life Cycle Assessment - based on BS EN 15978-2011. Life cycle stages marked with an X are included in this research

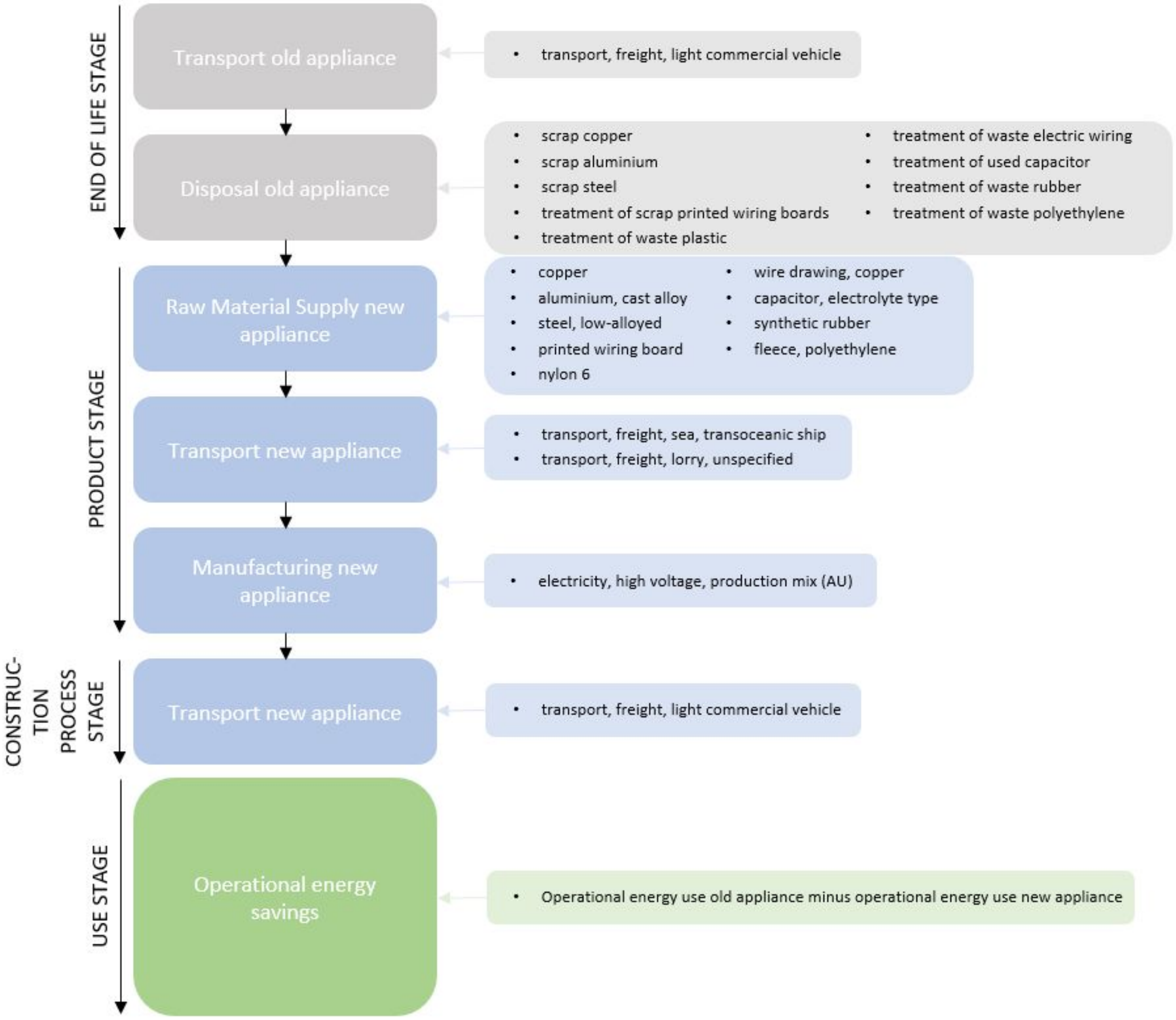
3.2. Methods

As this study evaluates energy savings from interchanging an old energy appliance to a appliance more efficient (six-star energy rated), a Life Cycle Assessment (LCA) approach was considered as the most suitable procedure to determine the environmental impact and the offsets of the new ducted gas heater. It further was enhanced by calculating the material composition and operational energy savings via Excel based on a distinguished assessment of a reference ducted gas heater and a source of energy data. The quality of the available data was scrutinised and assessed in detail. The data set consisted of 289 ducted gas heating upgrades and was linked to the properties' energy consumption. Only 107 properties that had received a ducted gas heating upgrade could be linked to energy consumption data of one year prior and after the heating upgrade. Energy consumption data which had no full year of energy data one year prior and after the upgrade were excluded. This includes any data which had been a false report within the year, meaning the gas meter was corrected. Of the remaining 107 ducted gas heating upgrades, the information provided from the old ducted gas heaters were assessed. As there were some relatively old ducted gas heaters, the brand and model numbers were not identifiable. Therefore, the weight of the old appliance could not be identified and the upgrade was excluded. That left 61 ducted gas heating upgrades which contains a full set of energy data one year prior and after the upgrade as well as information on the brand and model of the old appliance. The brand and model of the new appliance was provided for all ducted gas heating upgrades. The goal and scope definition of the assessed system was conducted in accordance with BS EN 15978-2011 and ISO 14040 recommendations [19]. *OpenLCA* software was used to assess the old and new appliances. The *Ecoinvent 3.4 cut-off* database was used as the primary source for the life cycle inventory (LCI) and primary energy saving data of the old and new ducted gas heating appliance were calculated in *Excel* and fed into *OpenLCA.* The system flow “heat, central or small-scale, natural gas” with the unit process “market for heat, central or small-scale, natural gas | heat, central or small-scale, natural gas | Cutoff, U – ROW” was used to convert the energy data into the impact categories. This would ensure that embodied and operational energy can be compared in the same categories. With the OpenLCA software, different LCA impact categories can be assessed. The IMPACT 2002+ method was chosen, which is a combination of IMPACTS 2002, Eco-Indicator 99, CML, IPCC and Cumulative Energy Demand [45]. The following impact categories have been assessed: global warming, ozone layer depletion, aquatic acidification, non-renewable energy, mineral extraction and carcinogens.

3.3. System boundaries

Figure 1 shows the LCI of the old and new ducted gas heaters, as well as the energy savings from the upgrade. The life cycle starts with the transportation of the old appliance to the waste facility and the disposal of the material, which will be further explained in 3.4.1. The deconstruction of the old appliance was omitted, as this was only done with equipment, not captured in the *Ecoinvent 3.4 cut-off database*, like ramps, tools, ladders and lighting. Additionally, the amount of tools would vary from upgrade to upgrade. Therefore, a distinct statement about the equipment used per upgrade could not be made. The end of lifecycle stage of the old appliance is followed by the manufacturing of the new appliance. The raw materials used in a ducted gas heater have been considered, as well as the required energy for manufacturing and transportation and are further explained in 3.4.2. For the construction stage, only transport has been considered and is further explained in 3.4.3. The installation of the new ducted gas heating system has not been further assessed due to the same reasons provided for the omission of the deconstruction phase (for the old system) above. The operational energy savings are based on data from both one year prior and after the ducted gas heating upgrade and were separately assessed. All details can be found in 3.4.4. Where possible, country specific data of the *Ecoinvent 3.4 cut-off* database were used. When this wasn’t possible, global data of the *Ecoinvent 3.4 cut-off* database were used.

Figure 1: Life cycle inventory of the old and new ducted gas heater



3.4. Data quality and sources

In terms of the data collection approach, primary and secondary data have been used. Furthermore, installation companies, manufacturers and recyclers were consulted to gain primary data but also to make reasonable assumptions when necessary. Additionally, assumptions are based on current literature whenever possible. The weight of each appliance, the operational energy used per heating upgrade and the IMPACT 2002+ results by life cycle stage are publicly available [46]. This should help readers to retrace the results and to further enhance research on this field.

3.4.1. End of life cycle stage

The transportion of the old appliance is based on a data set of 132 energy efficiency upgrades, which were part of the Energy Efficiency Improvement Scheme in Canberra, Australia. Nonetheless, this data is not specific to a ducted gas heater installation, this also includes other upgrades like air conditioning upgrades. All heating and cooling upgrades were undertaken by the same installation company. Based on this an average distance from the installation company to the recipient of the heating upgrade was used. The installation company would drive on average 53.61km within the Australian Capital Territory (ACT). It has been assumed that the same distance is needed to reach the recycling facility. The recycling facility is close to the installation company and therefore lies on the way.

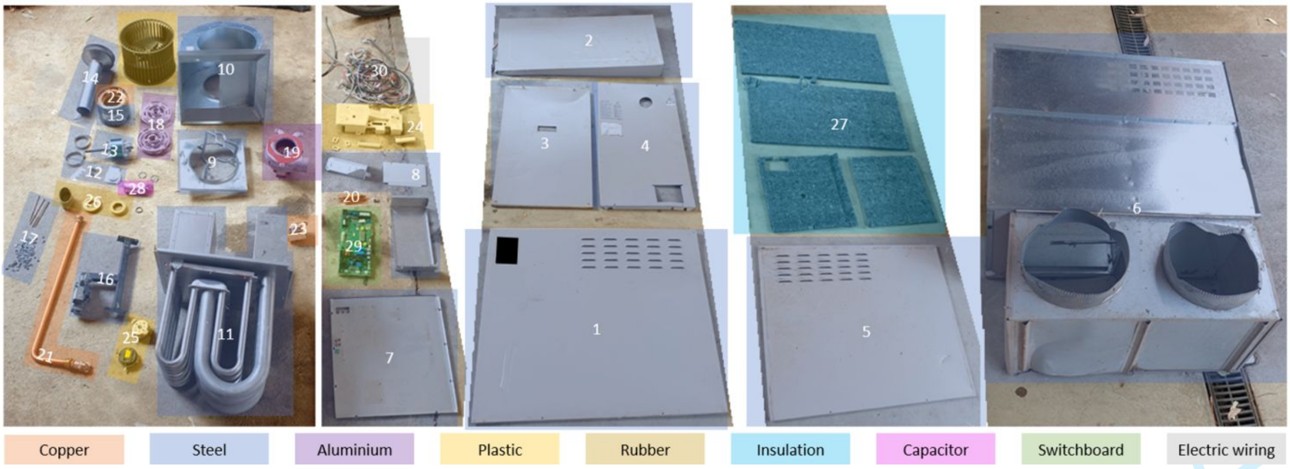
Based on interviews with recycling facilities, it was reported that the waste will be transported by truck from Canberra to a recycling facility in Sydney. The transportation by truck takes around 290km.

In addition, it was advised by the recycling facility that only metals would be recycled, and the remainder would go to landfill. Therefore, it has been assumed that the metals will end up as scrap metals wherefore the other materials will go to landfill. The scrap metals have been considered as outputs in OpenLCA, meaning what can be extracted from the old appliance. The further processing of the scrap metals was not considered, as there was no information available.

3.4.2. Manufacturing stage

The ducted gas heating system is a common heating solution in Australia [16]. It has one central ducted gas heater which heats the house via ducts to each room. As the length of the ducts and amount of ducts depend on the size and the amount of rooms in a house, the quantity of ducts has not been considered for this LCA. Only the ducted gas heating system was assessed. There has been limited research on ducted gas heaters and consequently there was no data available on the materials of ducted gas heaters. Therefore, an Australian manufactured ducted gas heater was deconstructed, and the different materials and components were quantified and analysed. A detailed view of the materials of the deconstructed ducted gas heater can be seen in Figure 2. The capacitator, switchboard and electric wiring have not been further deconstructed, as the weight of these were insignificant and are represented in the *Ecoinvent 3.4 cut-off* database, as seen in Figure 1. Copper has been listed as raw material in the *Ecoinvent 3.4 cut-off* database. For aluminium and steel cast alloy has been chosen due to its corrosion resistance, strength and hardness. The type of plastic could not be determined, it has been assumed that a plastic with a high melting point was used. Therefore, the plastic materials included in the ducted gas heater were modelled with a PA 6 plastic, which melts at 220°C [47]. Furthermore, it was assumed that synthetic rubber was used instead of a natural rubber base due to its durability. For the insulation fleece, polyethylene was chosen due to its heat resistance.

Figure 2: Material composition of deconstructed ducted gas heater



After the material had been classified, each part was weighed. The details of the measurements can be seen in Table 3. The total system weighs 69.67kg and 86.34% of the system is made of steel.

Material	No	Grams	Percentage
Steel	1	2,920	4.19%
	2	2,090	3.00%
	3	1,490	2.14%
	4	1,540	2.21%
	5	2,920	4.19%
	6	21,200	30.43%
	7	670	0.96%
	8	550	0.79%
	9	780	1.12%
	10	2,490	3.57%
	11	17,370	24.93%
	12	160	0.23%
	13	1,930	2.77%
	14	1,050	1.51%
	15	1,263	1.81%
	16	1,470	2.11%
	17	260	0.37%
Aluminium	18	390	0.56%
	19	1,690	2.43%
Copper	20	120	0.17%
	21	590	0.85%
	22	2,527	3.63%
	23	960	1.38%
Plastic	24	260	0.37%
	25	150	0.22%
	26	1,180	1.69%
Rubber	27	150	0.22%
Insulation	28	130	0.19%
Capacitor	29	160	0.23%
Switchboard	30	590	0.85%
Electric wiring	31	620	0.89%

Table 3: Material weight of ducted gas heater

Total		**69,670**	**100%**

The ducted gas heating system was used a reference for this research paper. The shares of the material were multiplied by 61 assessed ducted gas heating upgrades. Data from the new systems were based on primary sources and therefore the weight of each appliance was determined based on installation manuals of the manufacturer. The model and brand of the old ducted gas heater was retrievable and the weight of 61 old ducted gas heaters could be determined based on the manufacturer's installation manuals. The material share was then factored into the weight of the old and new ducted gas heating systems. The exact weight was documented in is publicly available [46].

As the deconstructed ducted gas heating system was Australian made, it has been assumed that the raw materials would come from Asia and would be transported to Australia by ship. The transportation journey by ship from Asia to Australia is estimated to be 10,850km. Furthermore, it is assumed that the raw materials are delivered from Melbourne harbour to the manufacturer by truck within a distance of 40km.

The manufacturing process takes place in Australia. Therefore, the Australian electricity production mix for Australia of the *Ecoinvent 3.4 cut-off database* was used. Nonetheless, primary data on the energy use of manufacturing ducted gas heating systems could not be found. A conservative approach was therefore chosen and it was estimated that 20 MJ/kg are needed to produce an appliance [48].

3.4.3. Construction stage

As for the deconstruction of the old ducted gas heater, the installation of the new ducted gas heater was done with minimal equipment not captured in the *Ecoinvent 3.4 cut-off* database like ramps, tools, ladders and lighting which were excluded from the LCA. The deconstruction was consequently not considered.

For the transportation it was assumed that the installation company received the appliance from the manufacturer in bulk per truck. The manufacturer is reportedly based in Melbourne. It is 705km from the manufacturing location to the installation company. Afterwards the appliance is transported to the recipient of the ducted gas heating upgrade by van, as advised by the installation company. As mentioned in "2.3.1 End of Life stage" the distance driven by van was calculated based on a data set of 132 energy efficiency upgrades. The van drives an average distance of 53.61km.

3.4.4. Use stage

Only B6 was considered as part of the use stage. The operational energy consumption is based on primary data. The data set included the gas consumption of 61 properties which received a ducted gas heating upgrade. This data includes the whole gas usage of the building and therefore could include other appliances like gas hot water systems or gas cook tops. Therefore, one year of gas consumption after the ducted gas heating upgrade was subtracted from one year of the gas consumption prior the ducted gas heating upgrade. This shows if there have been any increases or decreases in the gas usage which can be related to the ducted gas heating upgrade. While only considering the energy savings of the ducted gas heating upgrade, other gas based appliances can be excluded. A range of a year prior and after the ducted gas heating upgrade was chosen as it can be estimated that during this time period no further big investments, which would impact the gas usage of the building, were made. The primary data of one year prior and after the ducted gas heating upgrade have then been used as a reference value and multiplied by 20, as the life time of a ducted gas heater is 20 years [49]. Energy data which showed discrepancies have not been excluded from this research.

The operational energy savings of the 61 ducted gas heating upgrades are publicly available [46].

To assess the global warming, ozone layer depletion, aquatic acidification, non-renewable energy, mineral extraction and carcinogens impact categories, the energy savings were fed into *OpenLCA*. The *Ecoinvent 3,4 cut-off* “natural gas” dataset was used.

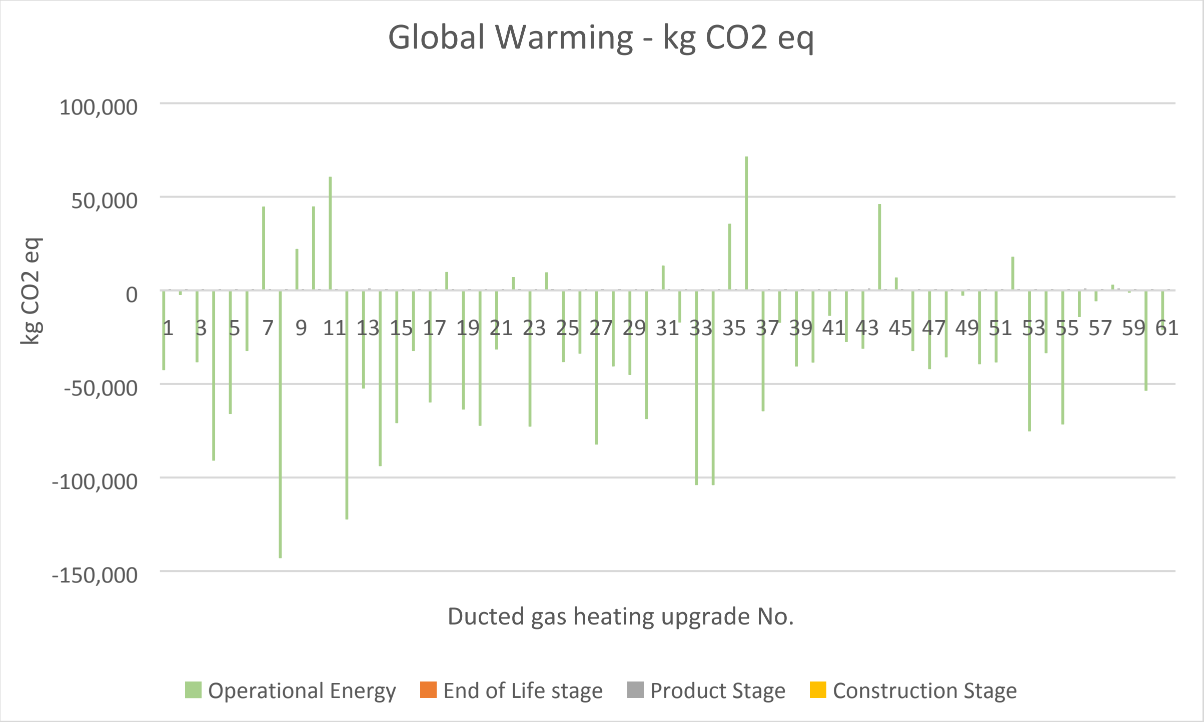
4. LCA Results reference ducted gas heating system

In summary, 61 ducted gas heating upgrades were assessed on the global warming, ozone layer depletion, aquatic acidification, non-renewable energy and mineral extraction impact categories. All 61 ducted gas heating upgrades were assessed based on the weight of the old and new appliances. To extract primary data, a ducted gas heater was deconstructed, and the materials were quantified and measured. This information was used as a reference to extrapolate approximate material values in all 61 ducted gas heating upgrades based on their weight. The presented results show the impact by stage and operation energy savings for each ducted gas heating upgrade. The detailed values of each impact category are publicly available [46].

4.1. Global warming

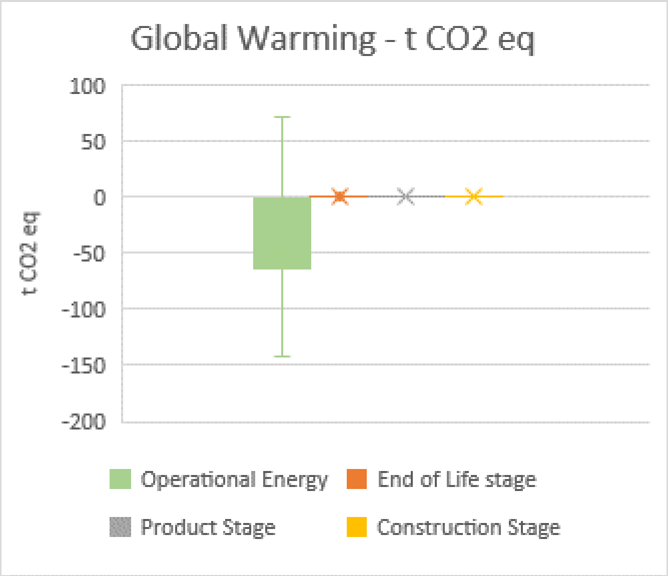
Figure 3 shows the global warming impacts by stage and the savings which were generated due to the ducted gas heating upgrade. The impacts contributed from the end of life, product and construction stages are minor in comparison to the savings generated with the ducted gas heating upgrade.

Figure 3: Global warming impacts and savings



In total the end of life stage of all 61 ducted gas heaters upgrades requires 507 kg CO_2 eq., the product stage of all 61 ducted gas heaters upgrades requires 40,358 kg CO_2 eq. and the construction stage requires 788.90 kg CO_2 eq. In total, the end of life stage of the 61 old appliances and the production and construction of the 61 new appliances account for 41,654 kg CO_2 eq. On the other hand, the operational energy savings of natural gas account for -1,926,679 kg CO_2 eq. The details of the split of each stage can be seen in Figure 4. Therefore, 1,885,025 kg CO_2 eq. were saved due to the 61 ducted gas heating upgrades. 14 ducted gas heating upgrades did not generate any operational energy savings as the gas consumption increased after the ducted gas heating upgrade. These accounted for 391,829 kg CO_2 eq. Nonetheless, in total the operational energy savings of all 61 ducted gas heating upgrades was higher than the increased usage. A net total of 2,318,508 kg CO_2 eq. were saved.

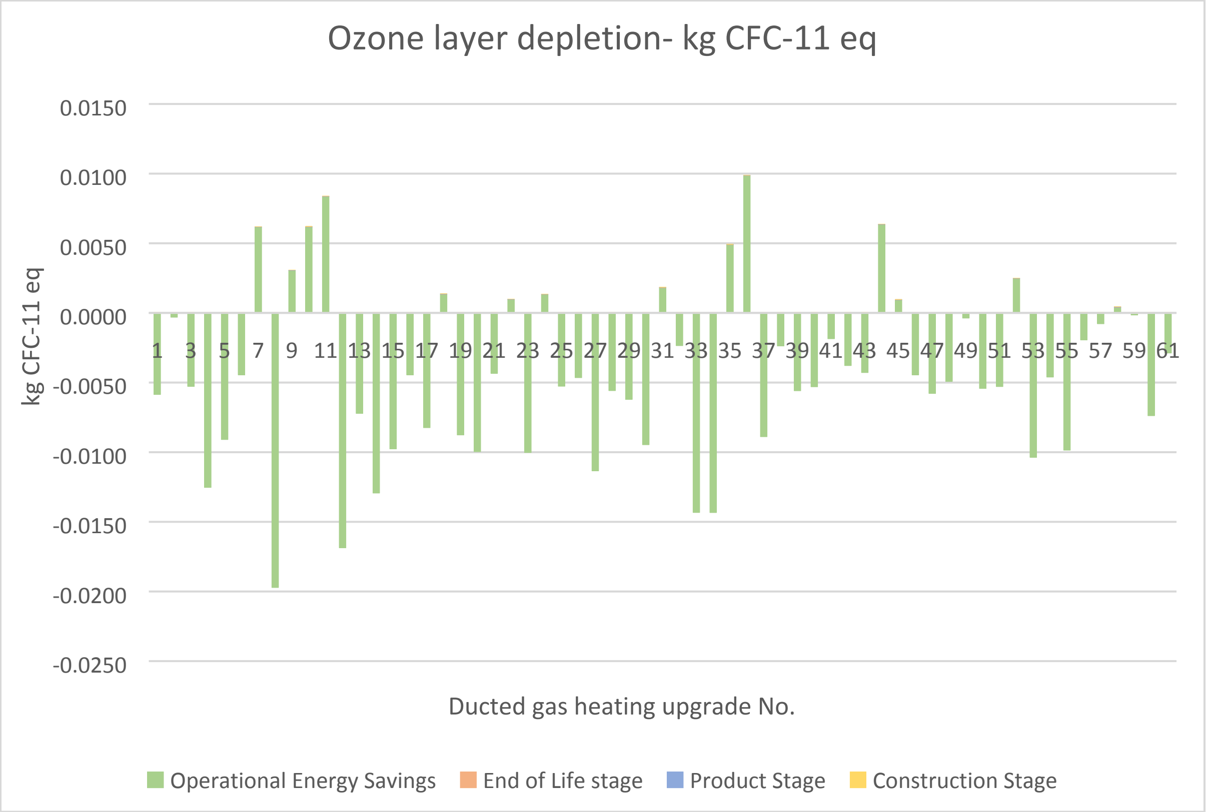
Figure 4: Global warming impacts and savings (Box and Whisker chart)



4.2. Ozone layer depletion

The ozone layer depletion in the old appliance's end of life cycle stage and in the new appliance's construction and product stage is rather low in comparison to the kg CFC-11 eq. savings generated through the operational energy savings, as seen in Figure 5. Nonetheless, is does the construction stage generate the highest kg CFC-11 eq. of all the stages with 0.009645 kg CFC-11 eq. for all 61 ducted gas heating upgrades. This is due to the long-haul transportation by truck. In total 705km are required. The construction required 40km of transport by truck and the end of life requires 290km of transport by truck. In total 0.011823 kg CFC-11 eq. are generated with the disposal of the old appliance and the production and construction of the new appliance. There have been 14 households which increased their gas usage and consequently impacted the depletion of the ozone layer. Nonetheless, the operational energy saved 0.265743 kg CFC-11 eq. Therefore, a total of 0.253919 kg CFC-11 eq. can be saved when replacing an inefficient ducted gas heater with a more efficient ducted gas heater.

Figure 5: Ozone layer depletion impacts and savings

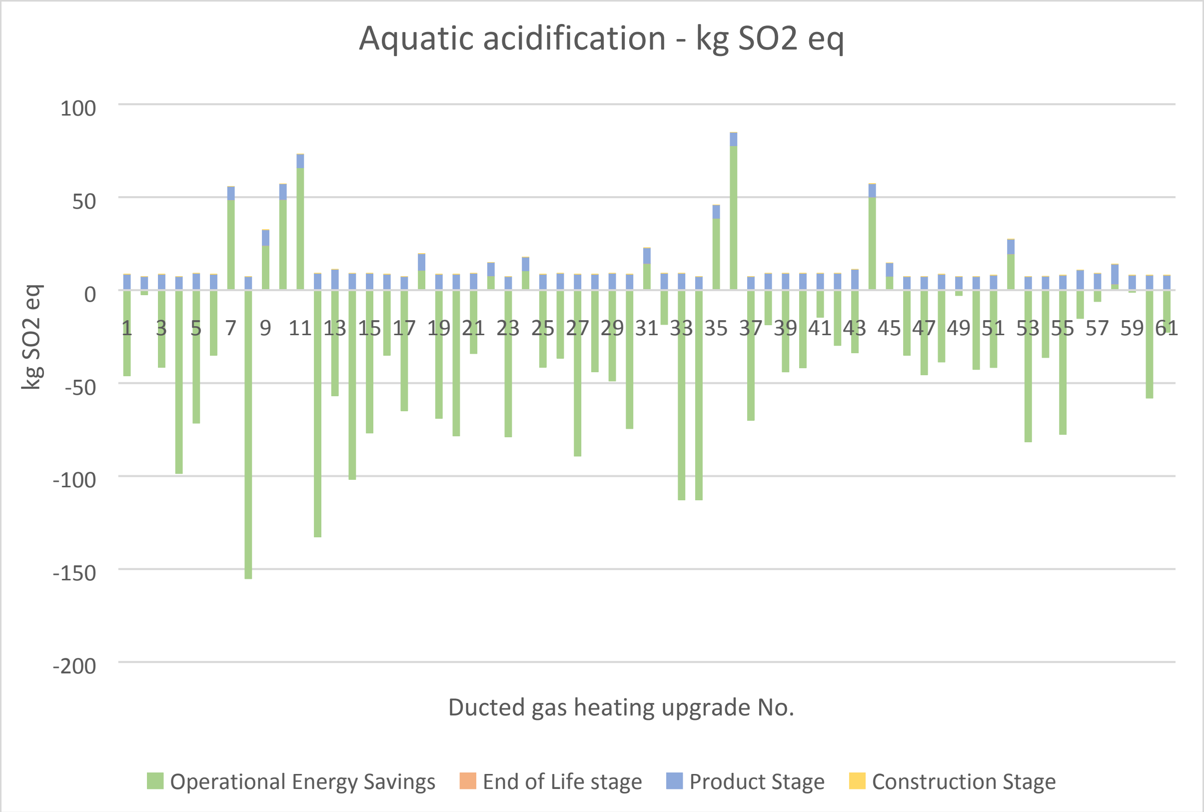


4.3. Aquatic acidification

Aquatic acidification shows the impacts of acidification to the aquatic by ducted gas heating upgrades. The operational energy savings offset the impacts generated by the disposal of the old appliance and the production and construction of the new appliance. The product stage contributes the most to the aquatic acidification with 507.20 kg SO2 eq. in total for all ducted gas heating upgrades. The construction makes up for 3.99 kg SO2 eq. and the end of life stage contributes 3.00 kg SO2 eq. This is due to the blasting and the copper production which impacts the aquatic acidification the most.

Figure 6 shows the impacts of acidification to the aquatic by ducted gas heating upgrades. The operational energy savings offset the impacts generated by the disposal of the old appliance and the production and construction of the new appliance. The product stage contributes the most to the aquatic acidification with 507.20 kg SO2 eq. in total for all ducted gas heating upgrades. The construction makes up for 3.99 kg SO2 eq. and the end of life stage contributes 3.00 kg SO2 eq. This is due to the blasting and the copper production which impacts the aquatic acidification the most.

Figure 6: Aquatic acidification impacts and savings

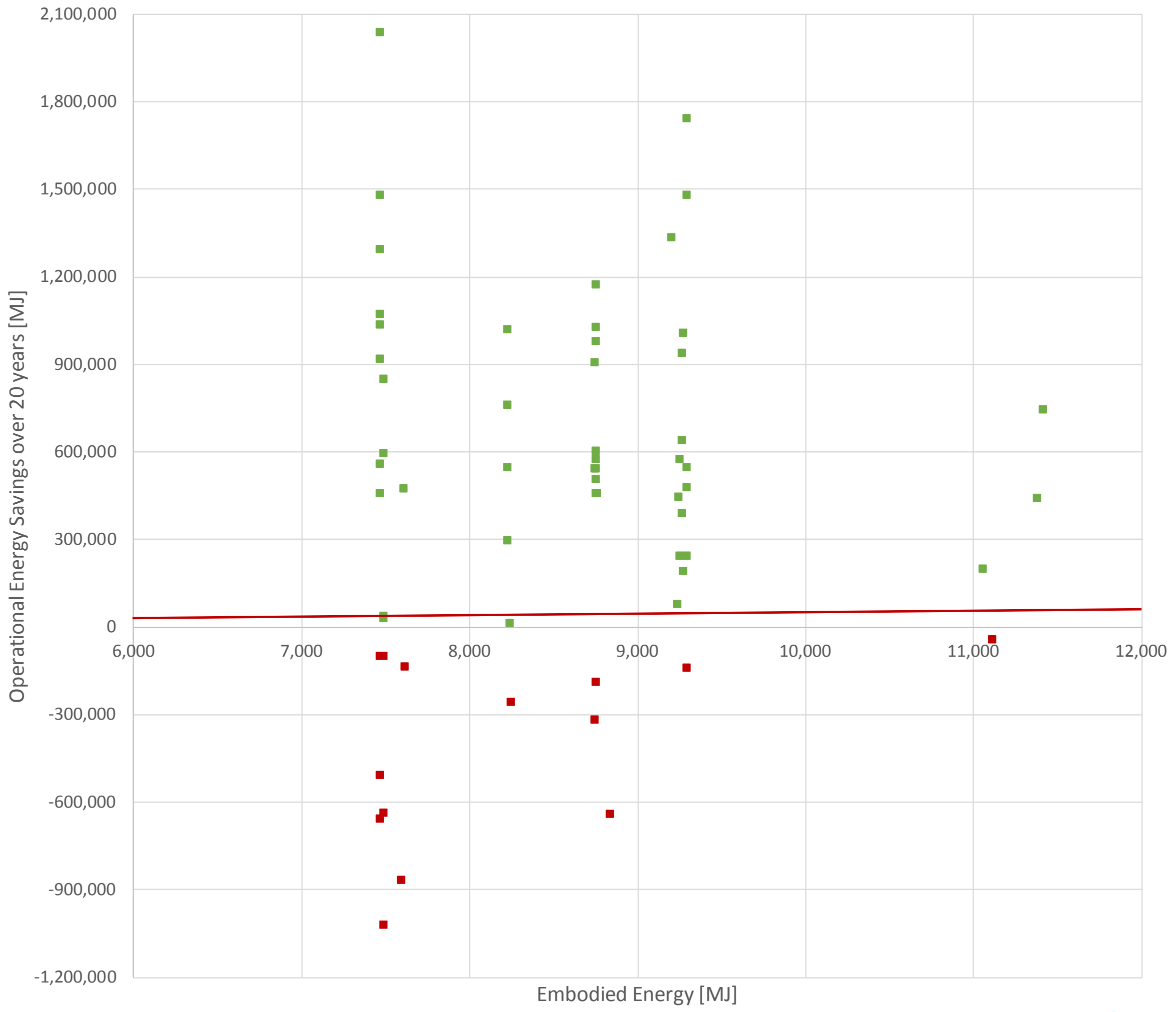


4.4. Non-renewable energy

As mentioned above the operational energy savings were based on primary data over one year. This has been multiplied by the lifetime of the appliance which is 20 years. The operational energy savings were equal with the impact of non-renewable energy which is measured in MJ. Figure 7 shows that only a minority of heating upgrades do not offset the embodied energy savings with its operational energy savings. 14 households increased their gas usage wherefore 47 households reduced their gas usage. The increased gas usage makes up for 5,587,409 MJ. The gas savings make up for 33,061,473 MJ. Even though there are 14 households which overall increased their gas consumption over the lifetime of 20 years, 27,474,064 MJ can be saved for all upgrades.

The increased gas usage may be due to individual households withbroken ducted gas heating systems which previously weren't working and were replaced with plug in electric heaters. This would then cause a spike in the electricity consumption but a reduction in the gas consumption. Therefore, with a ducted gas heating upgrade the gas use of the household would increase.

Figure 7: Embodied Energy in relation to the Operational Energy Savings



The 14 ducted gas heating upgrades have been further assessed on their energy consumption. In Table 4, it is shown that all properties which received a ducted gas heating upgrade and had an increase in their gas consumption reduced their electricity consumption after the ducted gas heating upgrade.

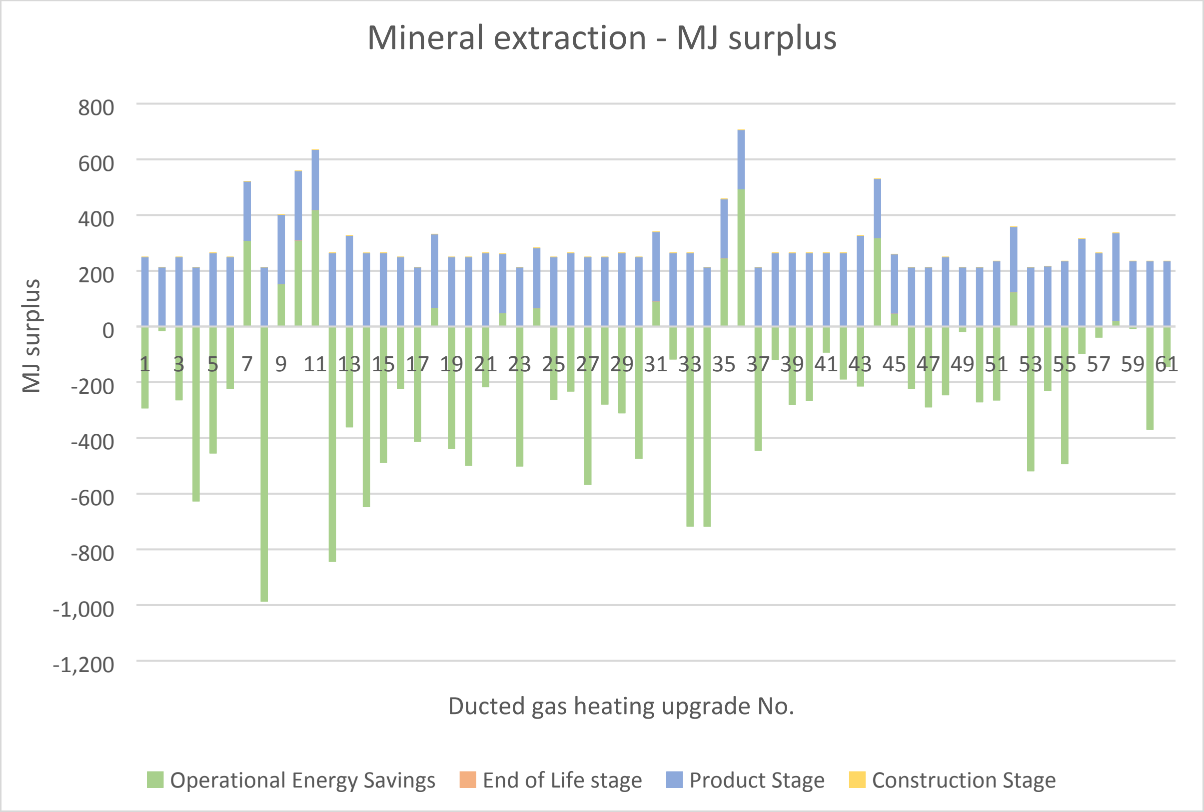
Table 4: Energy savings electricity and gas

	Electricity Consumption prior upgrade [MJ]	Electricity Consumption after upgrade [MJ]	Electricity savings [MJ]	Gas Consumption prior upgrade [MJ]	Gas Consumption after upgrade [MJ]	Gas savings [MJ]
DGH7506	27001.23084	5469.6905	-21531.5403	45251.86	77084.59	31832.7261
DGH3621	17016.28992	4849.642	-12166.6479	74555.41	90270.29	15714.8835
DGH5868	33582.32532	9854.2614	-23728.0639	83945.38	115847.5	31902.1053
DGH5972	88471.10808	22248.8835	-66222.2246	151451.8	194650.9	43199.1721
DGH6655	83853.02844	22491.3717	-61361.6567	83002.24	89938.67	6936.4265
DGH2064	34157.06424	9758.2468	-24398.8174	114623	119601.5	4978.5213
DGH5528	92921.09256	24835.0306	-68086.062	69464.74	76263.94	6799.2056
DGH5946	17049.99852	5961.8048	-11088.1937	45365.79	54703.34	9337.5503
DGH7818	87952.07808	18954.762	-68997.3161	34220.31	59530.05	25309.7407
DGH1764	57526.11324	10187.5045	-47338.6087	24836.89	75769.47	50932.5778
DGH7591	20389.01472	8126.7066	-12262.3081	13069.7	45868.07	32798.3738
DGH3954	33295.05756	8553.7378	-24741.3198	79392.38	84224.64	4832.2583
DGH.303	36795.2742	12960.1597	-23835.1145	261066.4	273790.3	12723.8895
DGH3087	27792.56268	7076.6505	-20715.9122	50965.98	53038.98	2072.9966

4.5. Mineral extraction

The mineral extraction is not offset by the operational energy savings generated from the ducted gas heating upgrade. The operational energy savings contribute in total to 13,301.45 MJ savings, the embodied energy still requires a total of 14,930.09 MJ of mineral extraction. In total 14,863.48 MJ are used for the production of all 61 ducted gas heaters. This accounts for the highest share. The construction requires 33.55 MJ and the disposal and transport of the old appliance requires 33.06 MJ. The copper mining has the highest impact on the mineral extraction followed by the ferronickel production.

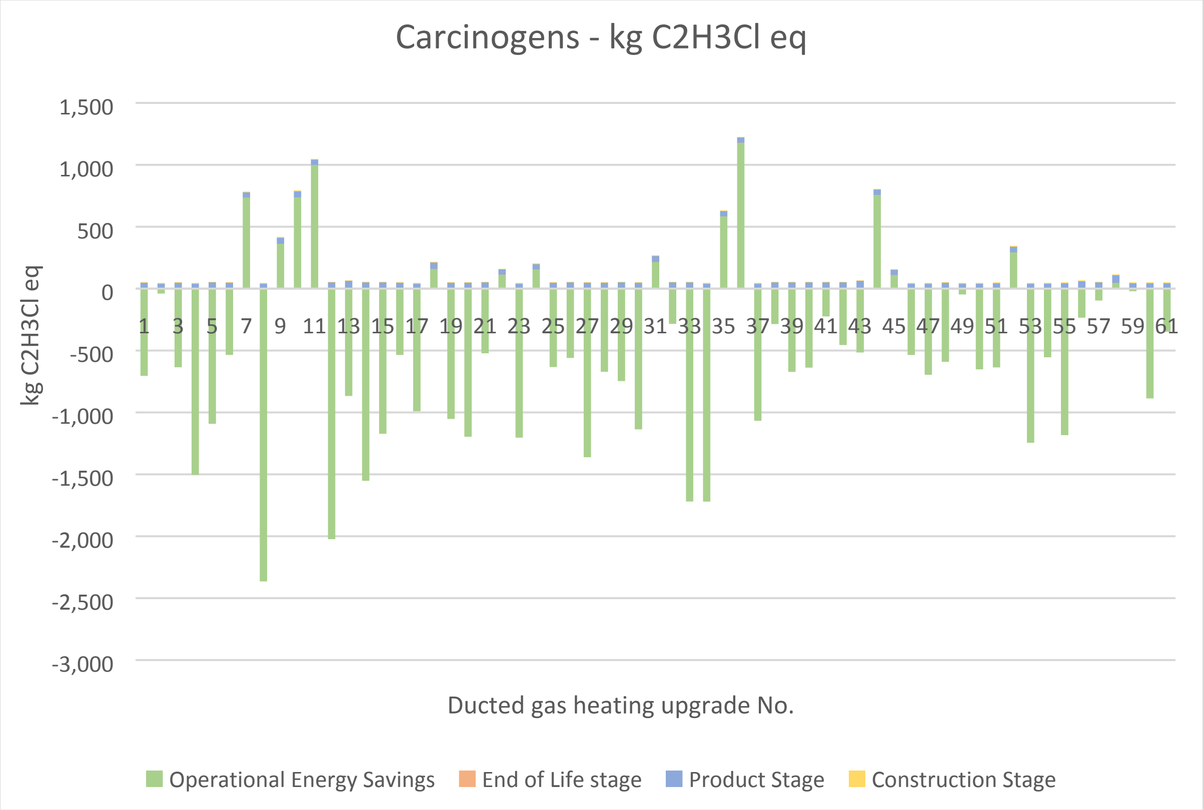
Figure 8: Mineral extraction impacts and savings



4.6. Carcinogens

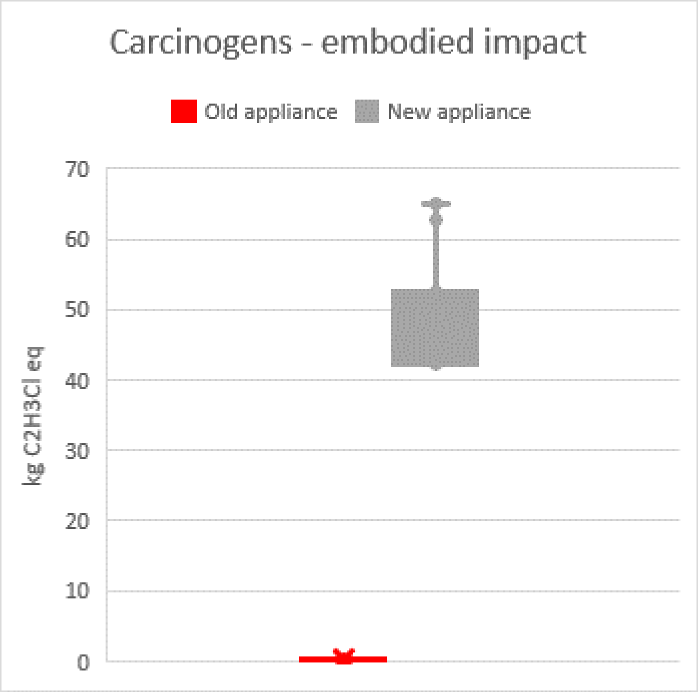
As seen in Figure 9, the carcinogens impact is heavily offset by the operational energy savings of the ducted gas heater. While the disposal of the old appliance and the production and construction of the new appliance require 2,969.44 kg C2H3Cl eq. the operational energy savings total 28,870.73 kg C2H3Cl eq. The savings make up nearly 10 times as much kg C2H3Cl eq. as was generated.

Figure 9: Carcinogens impacts and savings



When isolating the operational energy savings from the embodied energy of the old and new appliances it can clearly be seen in Figure 10 that the carcinogens impacts are significantly higher for the new appliances. While carcinogens of the old appliances are predominately impacted by hydrocarbons, which are admitted to the air due to the transportation, the new appliances are predominately impacted on arsenic and hydrocarbons emissions to air. The arsenic is mainly generated from the wiring board production while the hydrocarbon is mostly generated from steel production.

Figure 10:Carcinogens- embodied impact of old and savings



4.7. Average results

The above impact categories represent the impacts by ducted gas heating upgrades. The average impacts by category can be seen in Table 5. The average operational energy savings offset the embodied energy in the categories: global warming, ozone depletion, aquatic acidification, non-renewable energy and mineral extraction. Mineral extraction is the only impact category where the operational energy savings cannot offset the embodied energy. The mineral extraction of the embodied energy is 1,628.64 MJ higher than the operational energy savings.

	Operational Energy stage	**End of Life stage**	**Product stage**	**Construction stage**
Global warming - kg CO_2 eq	-1,926,679.01	506.86	40,357.76	788.90
Ozone layer depletion - kg CFC-11 eq	-0.004356	0.000002	0.000034	0.000158
Aquatic acidification - kg SO2 eq	-2,092.11	3.00	507.20	3.99
Non-renewable energy - MJ primary	-450,394.49	160.93	8,195.36	14,616.33
Mineral extraction - MJ surplus	-13,301.45	33.06	14,863.48	33.55
Carcinogens - kg C2H3Cl eq	-31,840.17	11.88	2,944.79	12.77

Table 5: The average values of the impact categories by stage

5. Discussion

Following common energy efficiency upgrades it can be said that gas heating is not the most sustainable choice of heating. In 2019 a dwelling in the ACT accounted for 165,100 kg CO_2 over its lifetime [50]. In comparison the annual CO_2 eq. savings of the ducted gas heating upgrade account for 94,251 kg CO_2 eq. While heating makes up for around 20% to 50% of a buildings energy consumption [17] the upgrade to a more efficient ducted gas heating system will reduce carbon emissions despite its embodied energy. Despite previous literature on this topic, this research paper uses real energy consumption data of 61 properties which received a ducted gas heating upgrade. Therefore, different behavioural heating preferences and energy uses are included. This strongly shows that real data of the operational energy usage are important to determine whether the environmental impacts of embodied energy can be offset, as there have been 14 properties which increased their gas usage after the upgrade. Considering 61 heating upgrades show that a large spectrum of appliances is necessary to exclude any variances.

Nonetheless, it is important to know the life cycle impact of a ducted gas heater to make a conscious decision for a more sustainable heating, and evidently cooling, alternative. While considering the environmental impact of a ducted gas heater over its lifetime it can be compared to other building appliances. As this study showed the operational energy savings offset the embodied impacts, except the impact category of mineral extraction (MJ surplus). Nonetheless, the non-renewable energy savings generated through the upgrade also offset the impacts of the mineral extraction. On average 1,885,025.49 MJ of non-renewable energy can be saved while upgrading to a more efficient ducted gas heating upgrade. The surplus of 1,628.64 MJ of mineral extraction makes only up for 0.1%. Therefore, the environmental benefits outweigh the impacts generated by the production of a new ducted gas heater.

6. Conclusion

A ducted gas heater has a significant impact on our environment over its lifetime. While there is currently limited research on building appliances this research paper clearly stated that there is a need for further research on building appliances and knowing their environmental impact. Assessing appliances via an LCA establishes a framework where appliances can be systematically compared helps to make them comparable and will help decision makers make an informed choice for more environmentally friendly alternatives.

This study assessed the environmental impact of an Australian ducted gas heater. While only limited research is available, a ducted gas heater was deconstructed and assessed on its material and quantities. Furthermore, installation companies, manufactures and recyclers were contacted to gain primary data but also to make reasonable assumptions when necessary. After the data collection component, the system was then assessed via an LCA. The results clearly show that the operational energy savings offset the impacts generated with the end of life treatment of the old appliance as well as the product and construction stage of the new appliance (global warming, ozone layer depletion, aquatic acidification, non-renewable energy, carcinogens). This is due to the high use of natural gas during its lifetime. In average 1,885,025.49kg CO_2 eq., 1,577.92 kg SO2 eq, 425,793.23 MJ and 28,870.73 kg C2H3Cl eq can be saved. Only the mineral extraction cannot be offset by the operational energy savings. Conversely, 0.0042 kg CFC-11 eq. get released to the atmosphere.

The results show that the embodied energy only makes up for a small portion. The highest impact remains in the actual operational energy. 23% of the households receiving a ducted gas heating upgrade increased their operational energy use after the upgrade. This can be due to the rebound effect and therefore a heating upgrade should also improve the educational awareness on how to avoid the inefficient usage of a system. Also, it can be due to a broken ducted gas heating system which has not been used prior to the upgrade while electric portable heating systems have been used instead. Nonetheless, the overall operational energy savings outweigh the increased energy use by 27,474 GJ over the lifetime of the appliance (20 years). Therefore, it can be assumed when using a more efficient gas heater with a lower gas use that this would significantly reduce the environmental impacts. Moreover, a ducted gas heating system can also be replaced with a ducted reverse-cycle air conditioner when the cavity space allows for the normally larger ducts to have enough space. It would also be of interest to compare the environmental impact of replacing a ducted gas heater with a more efficient heating and cooling system to the impact of changing the source of heating from natural gas to electricity.

Nonetheless, is this study limited is to the Australian market and is influenced by economic, social, political, legal and environmental pressures unique to Australia. As in Australia, the typical type of heating is reverse-cycle heating, followed by gas heating, this might not apply to other countries. Also, the study has considered an Australian manufactured ducted gas heater, which reduces the impact on transportation emissions. While having tried to use predominately primary data, still assumptions still had to be made which might affect the results of this study. It would be recommended to replace the assumptions with real data when these become available and to also assess appliances which are manufactured outside of Australia.

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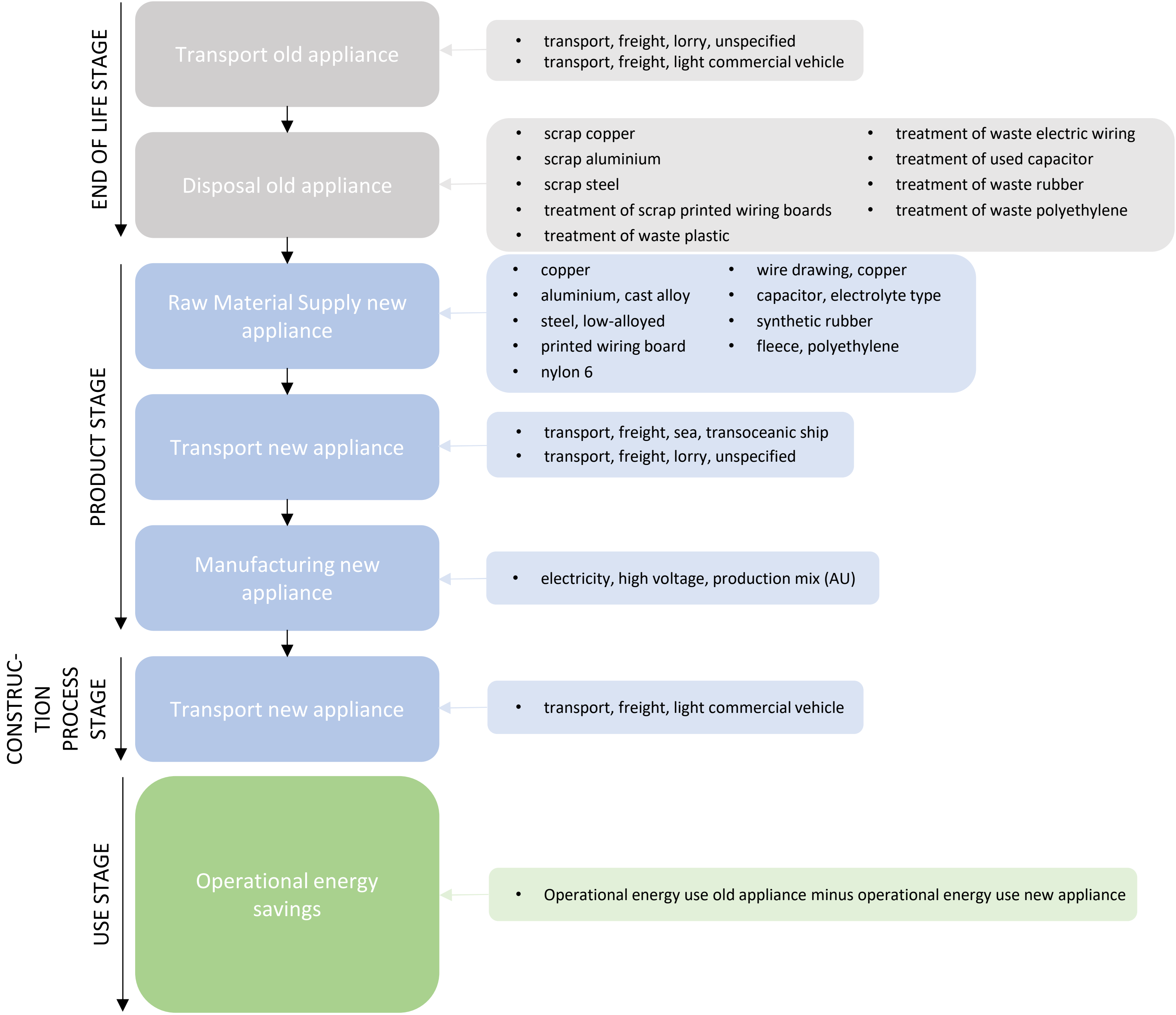
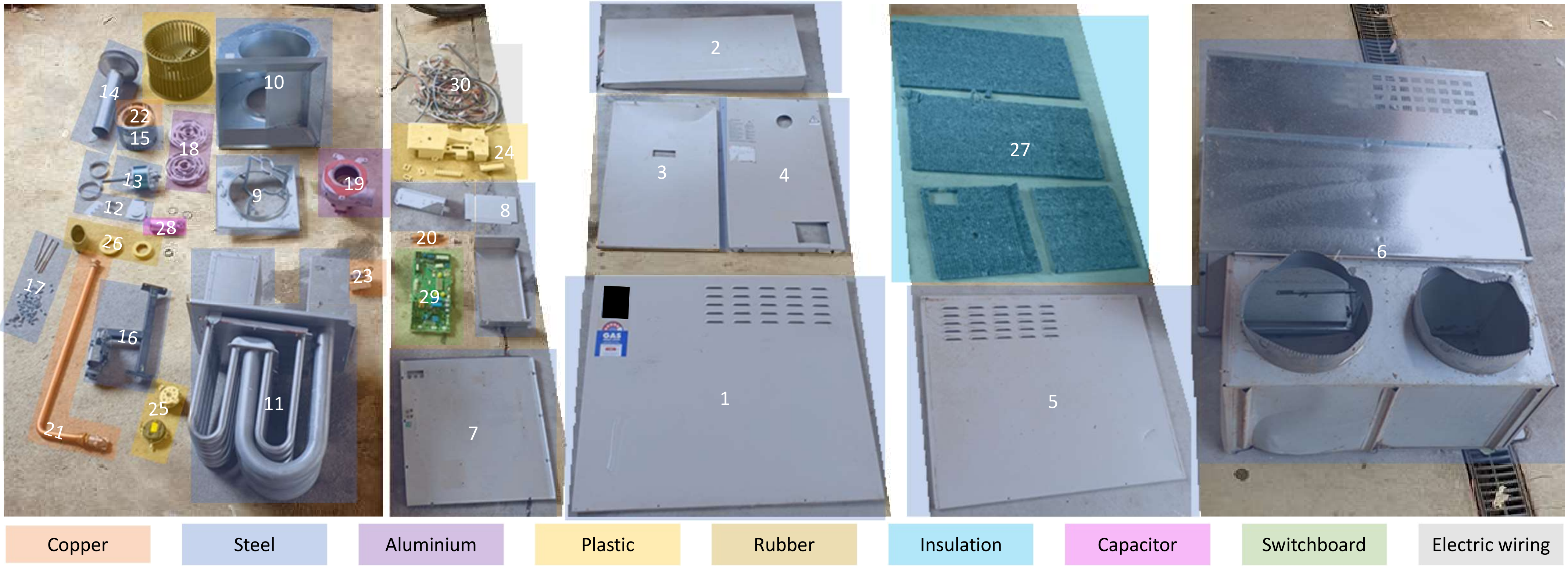

END OF LIFE STAGE
Transport old appliance
transport, freight, lorry, unspecified
transport, freight, light commercial vehicle
Disposal old appliance
scrap copper
scrap aluminium
scrap steel
treatment of scrap printed wiring boards
treatment of waste plastic
treatment of waste electric wiring
treatment of used capacitor
treatment of waste rubber
treatment of waste polyethylene
PRODUCT STAGE
Raw Material Supply new appliance
copper
aluminium, cast alloy
steel, low-alloyed
printed wiring board
nylon 6
wire drawing, copper
capacitor, electrolyte type
synthetic rubber
fleece, polyethylene
Transport new appliance
transport, freight, sea, transoceanic ship
transport, freight, lorry, unspecified
Manufacturing new appliance
electricity, high voltage, production mix (AU)
CONSTRUCTION PROCESS STAGE
Transport new appliance
transport, freight, light commercial vehicle
USE STAGE
Operational energy savings
Operational energy use old appliance minus operational energy use new appliance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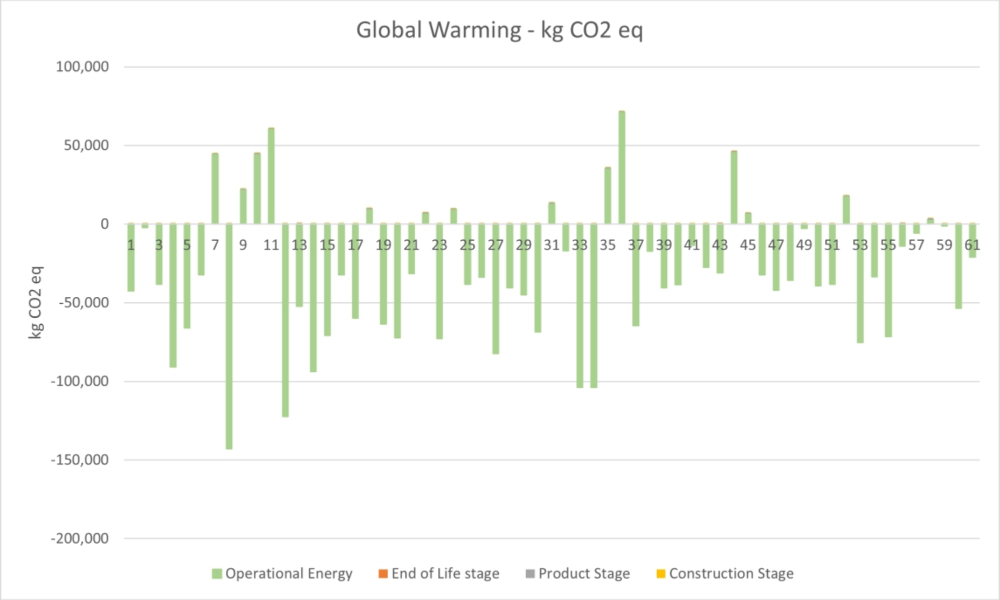

Figure 3: Global warming impacts and savings

496x298mm (130 x 130 DPI)

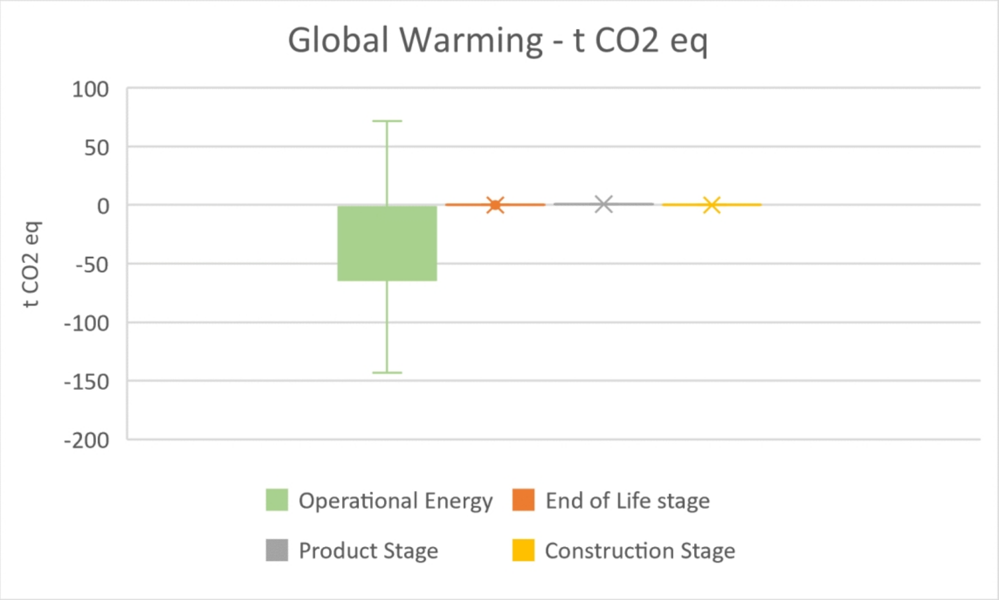

Figure 4: Global warming impacts and savings (Box and Whisker chart)

322x193mm (130 x 130 DPI)

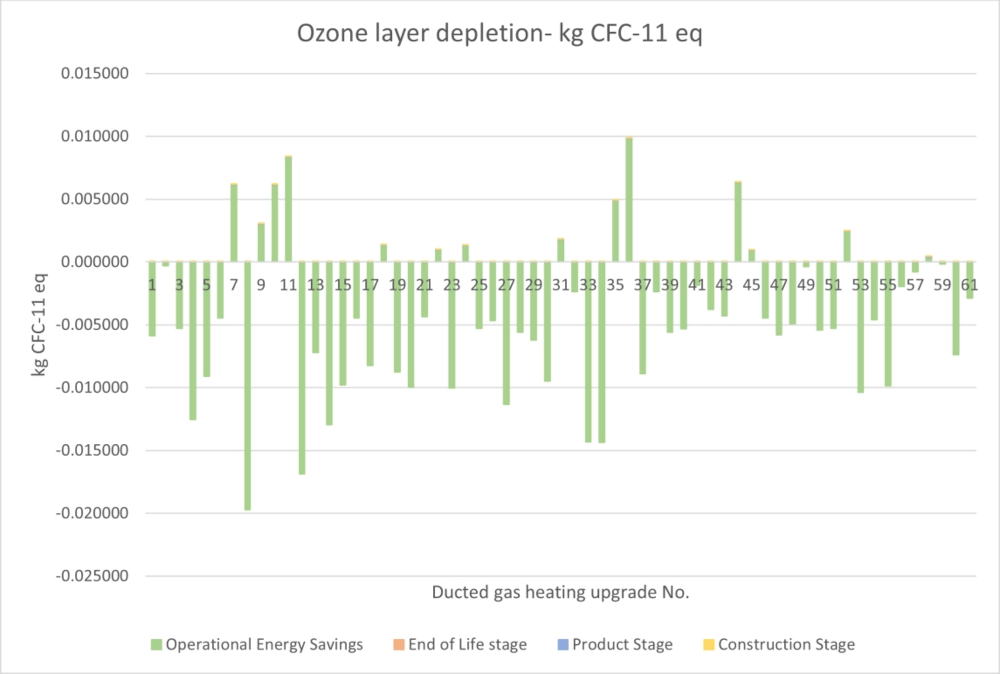

Figure 5: Ozone layer depletion impacts and savings

451x305mm (130 x 130 DPI)

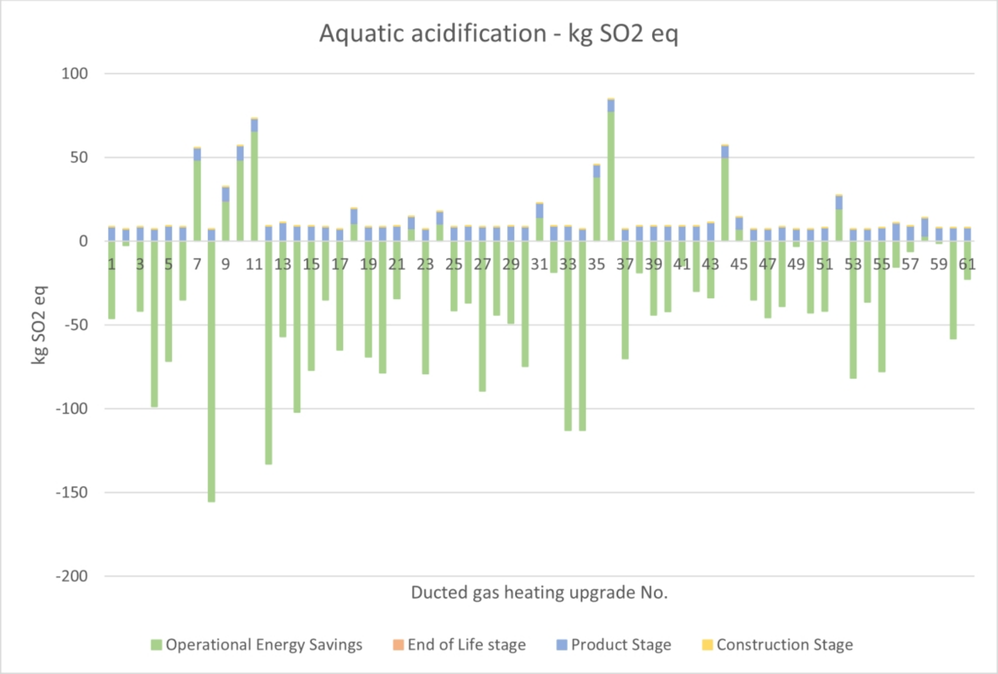

Figure 6: Aquatic acidification impacts and savings

452x305mm (130 x 130 DPI)

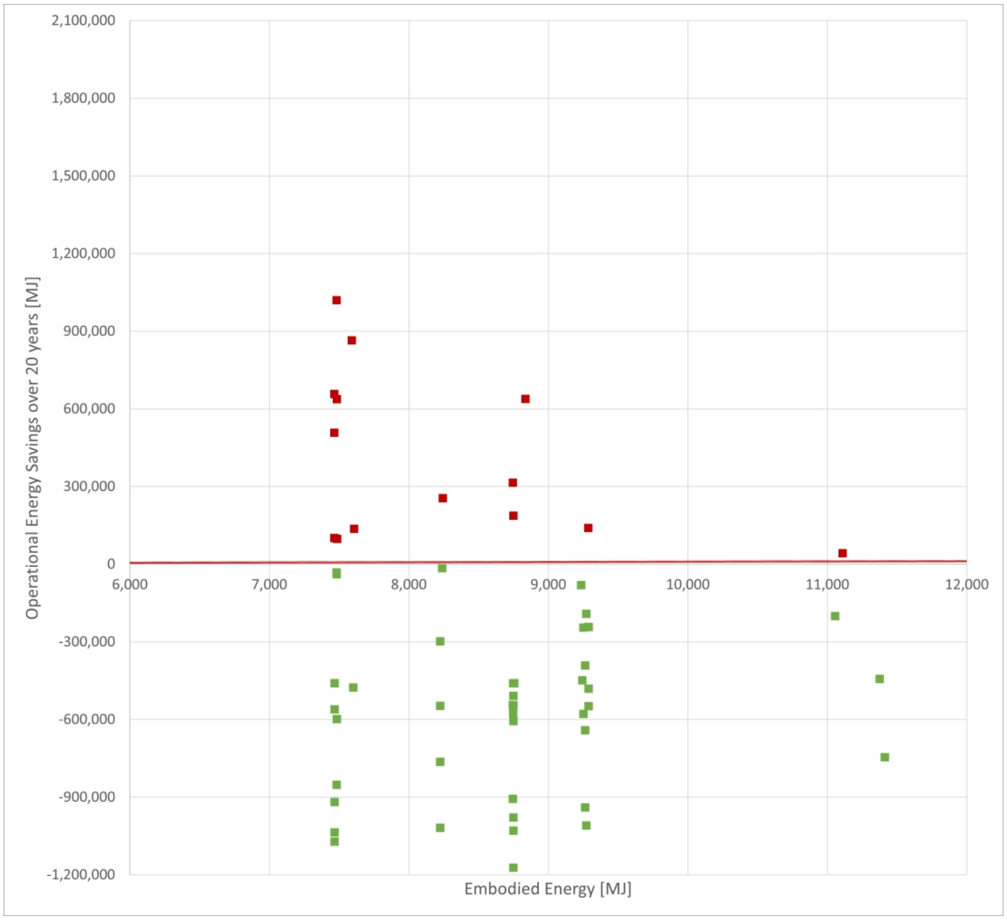

Figure 7: Embodied Energy in relation to the Operational Energy Savings

680x621mm (130 x 130 DPI)

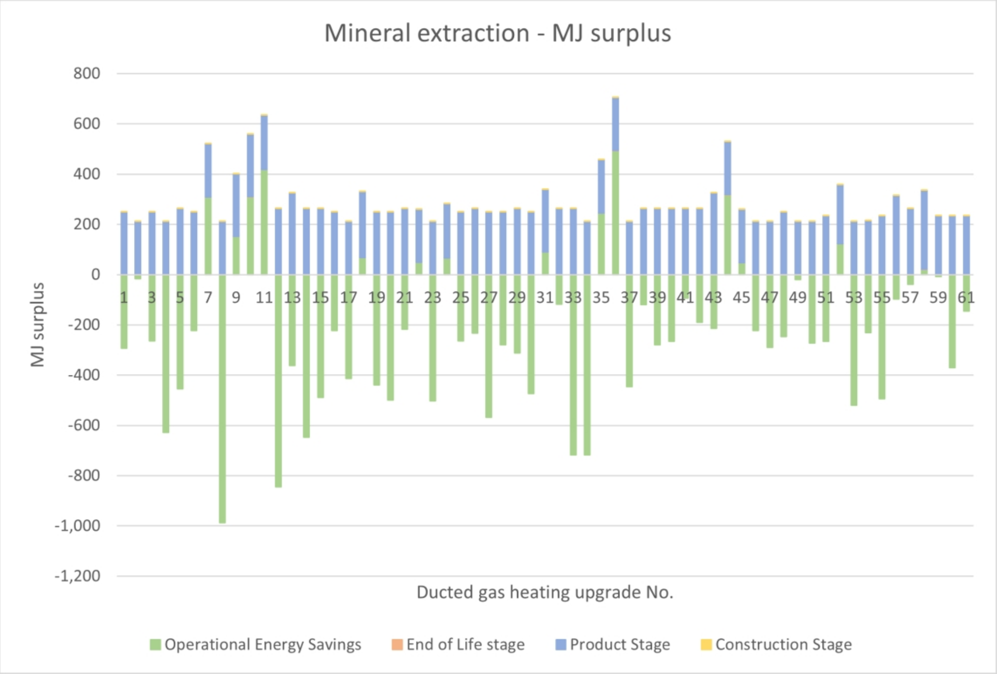

Figure 8: Mineral extraction impacts and savings

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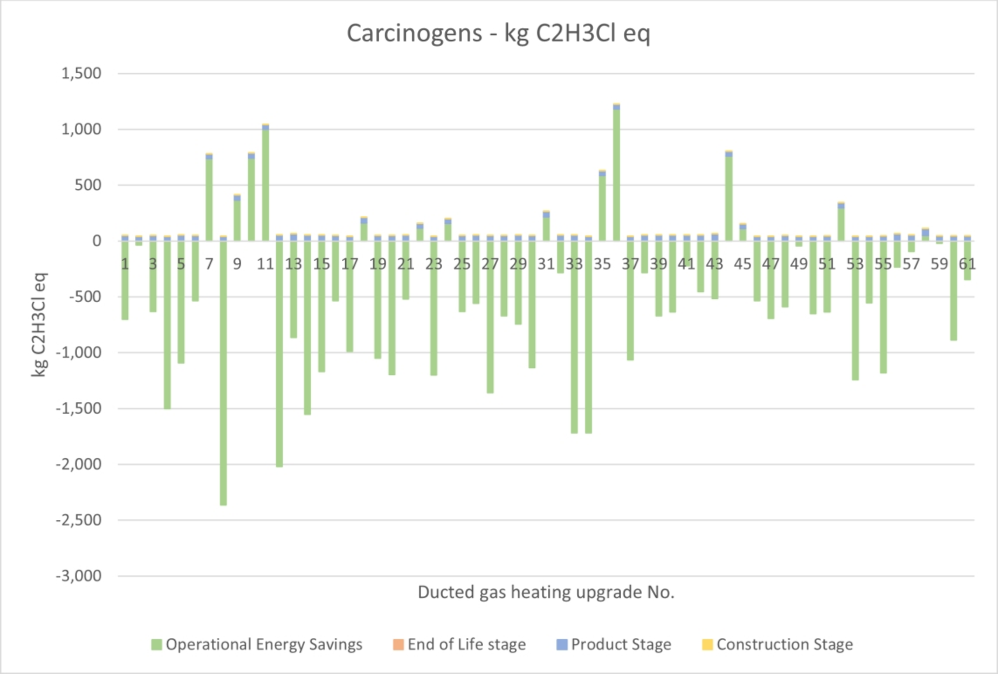

Figure 9: Carcinogens impacts and savings

452x305mm (130 x 130 DPI)

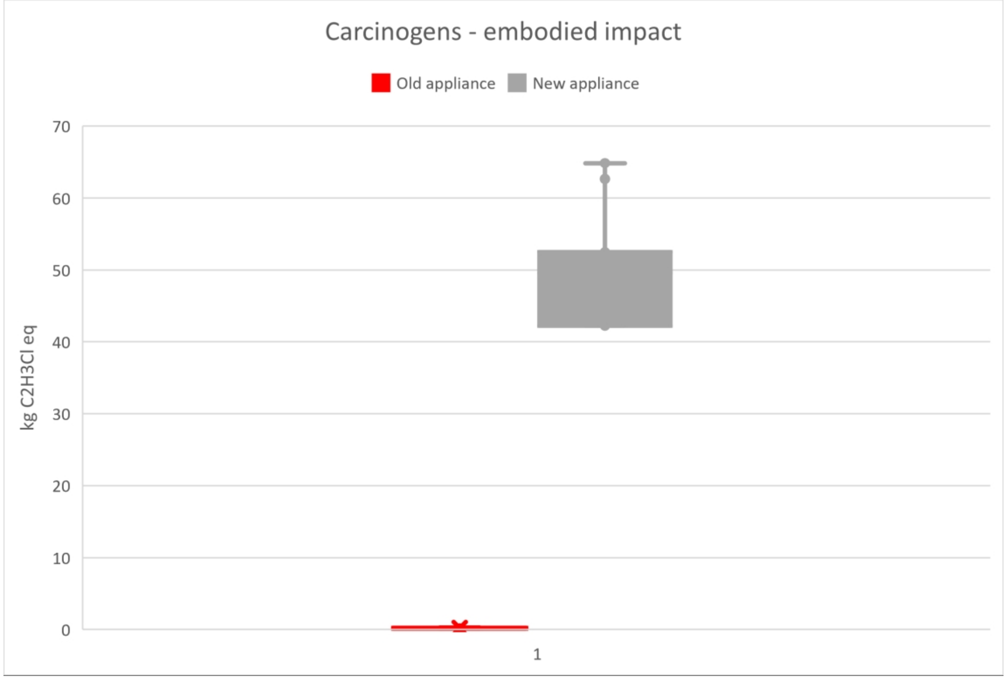

Figure 10: Carcinogens- embodied impact of old and savings

450x304mm (130 x 130 DPI)