Environmental impact assessment of a rotary compressor in Thailand based on life cycle assessment methodology

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Abstract

This paper aims to evaluate and identify the environmental performance of a fixed speed rotary compressor produced in Thailand throughout the whole compressor life cycle, in comparison with an inverter twin rotary compressor. This study covers all life cycle stages, including raw material production, manufacturing, compressor use, final disposal, and all related transport. This research is performed in accord with ISO 14040/14044 standards. Life cycle assessment methodology is employed in this research. The investigation results are showed in terms of ten impact categories using the ReCiPe midpoint (H) V1.13 method. The ten environmental impact categories are investigated: climate change (CC), ozone layer depletion (OD), terrestrial acidification, freshwater eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, water depletion, metal depletion (MD), and fossil depletion. The results show that the use stage of the compressor has the largest contribution to the environmental impact due to most energy being consumed in this stage. The raw materials production stage is important due to the contribution from copper and steel production. In the manufacturing stage, the electricity consumption in the machining process is the most contributing process. While the end-of-life stage, the R22 refrigerant emitted to the atmosphere is a significant effect on the CC and OD impacts, whereas metal recycling is an environmental benefit in terms of the MD category due to the reduction in virgin material requirements. The shifting from a fixed speed rotary compressor with R22 refrigerant to an inverter twin rotary compressor with alternative refrigerants, the results show that complete termination of ozone layer depletion affected by the R410A and R32 refrigerants are confirmed. Also, the inverter twin rotary compressor with R410A and R32 refrigerant can reduce impacts in all impact categories, in the range of 21.7–53.1% and 28.7–53.2%, respectively. Results demonstrated that the use stage should improve energy efficiency due to it resulting in the largest contribution to the environmental impact, which is induced by electricity consumption. To develop the new types of the compressor with high energy efficiency, such as a twin rotary compressor with the inverter system to control the operation, is the best option in order to reduce the environmental impact from the use stage of the compressor.

Keywords Rotary compressor · Life cycle assessment · Climate change · Terrestrial acidification · Fossil depletion

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1 Introduction

Most manufacturing processes are usually focused on product quality and cost. The environmental issues in a factory were aimed mainly at the “End of Pipe” treatment in order to comply with environmental regulations. Nowadays, environmental concern has become another driving force in global business, such as the producer's responsibility and environmental labeling [22]. Furthermore, the International Organization for Standardization (ISO) has been working on standardizing environmental management systems and tries to find solutions for environmental problems. The ISO activities have driven industries in worldwide to increase the environmental performance of a product and service. The European Union (EU) is the key player in these activities. Some evidence is legislation and directives such as Integrated Product Policy (IPP), Waste from Electrical and Electronic Equipment (WEEE) as well as producer responsibility obligations and sustainable development pressure. For purchasers, they are increasingly more concern over the impacts of a product to health and environment, as well as the quality of the product. As a result, they tend to buy products that are more environmentally friendly. For these reasons, some industries have tried to reduce the environmental impacts of their products and operations. To properly evaluate the environmental impacts of a product the whole life cycle of that product should be considered.

Life Cycle Assessment (LCA) is a potential tool to provide a thorough analysis of a product that covers its whole life cycle and can identify many of the potential impacts. However, this method needs accurate background data to effect the highest efficiency [11]. LCA is a worldwide environmental management tool due to its various useful applications. For example, it can be used by industry for green product development and long term strategic planning. Customers can benefit from LCA by using information on type III Eco-labels to selectively purchase goods and services [13]. Governments can also utilize LCA to support lifecycle-thinking uses and to promote relevant activities to private sectors.

Nowadays, an air conditioner is considered as necessary electrical equipment for every office building and household. It is also one of the appliances with the highest electricity-consumption. It consists of four major components: an evaporator, a compressor, a condenser, and an expander. These four parts are connected in a close system. The compressor is the essential part for driving refrigerant into the cooling system [17]. The export value of the air-conditioners from Thailand was approximately US\$ 4819.8 million in the year 2017, and

increased to US\$ 5365.5 million in the following year [2]. Furthermore, about 46% of resident electricity consumption resulted from air-conditioner usage [6]. This number was quite significant since electricity generation has direct impacts on the environment.

When considering the environmental aspect of air-conditioner, there are several studies that evaluated the greenhouse gases (GHGs) and other environmental impacts of air-conditioner and compressor based on the LCA method. The literature review has comprehensively investigated are summarized in Table A1 from the Electronic Supplementary Material. Yanagitani and Kawahara [26] study the LCA of air conditioners with an alternative refrigerant in Japan. Gheewala and Nielsen [7] studied the environmental impacts of central and individual air-conditioning systems using the LCA technique. Zanghelini et al. [27] evaluated the environmental impacts of a reciprocating air compressor in Brazil from cradle-to-grave and compared three waste management alternatives. The results indicated that the hotspot of the product system occurs in the use phase, due to the high demand for energy during its long life span. By removing the use phase from the LCA result, we found that for all categories remanufacturing has the best environmental performance, followed by recycling and landfilling. Shi et al. [23] presented the energy consumption and environmental emissions of a scroll compressor in China based on the cradle-to-grave approach, the results showed that the compressor use stage in the life cycle consumes the most energy and exerts the strongest environmental impact, followed by the stages of raw material production, and component manufacturing. Almutairi et al. [1] investigated the LCA and economic analysis of residential air conditioning in Saudi Arabia., the results showed that the use phase represented the largest share of the environmental impacts, the copper and steel production dominated in the manufacturing phase impact, and the end-of-life (EOL) phase resulted in environmental benefits by reducing the need for virgin materials. Peng et al. [18] applied the LCA to an 18.4 MW class domestic large-scale centrifugal compressor in China, the result showed that the usage, raw material production, and manufacturing are the top three contributors to the environmental impact. Ross and Cheah [21] studied a sensitivity analysis of Singapore's air conditioning systems, focusing on greenhouse gas emissions, the results showed that the use stage dominated the life cycle and the uncertainty analysis showed a reasonable reduction in the impact through changes in user behavior. Schleicher et al. [22] compared the LCA of air conditioners and found that single-split air conditioners operating in a moderate climate zone and make use of R-290 can typically save up to 30% GHG emissions as compared to devices that make use of R-410A and are in tropical climate

zones. This GHG saving typically amounts up to almost 50%. Peng et al. [19] developed a dynamics modeling to predict the future energy structure in China until 2030, developed the dynamic characterization factors (CFs) of global warming potential (GWP) and conducted a case study on a large-scale centrifugal compressor, that showed the GWP under the electricity variation was lower than those of conventional LCA, and the GWP under dynamic CFs would be deducted by 14.5% more.

Many previous studies have focused on evaluating the effect of refrigeration systems on energy and the environment, and were performed to comply with the LCA framework requirements, improve inventory data, and quantify the production stage. However, published studies lack detailed data on LCA information for reference to the development of an environmentally-friendly product and most LCA studies did not attempt to quantify sensitivity. To conclude, the electricity consumption during the compressor use stage is expected to be a key uncertain parameter due to temperature rise affects human economic activities and electricity consumption. Therefore, this study aims to evaluate the environmental performance of a fixed speed rotary compressor for air-conditioners in Thailand using LCA methodology and to suggest improvement options to reduce the environmental impacts. This study also estimates the influence of room temperature settings on the electricity consumption of compressors due to the user behaviors variability for sensitivity analysis.

2 Methodology

This study applies an LCA framework, in compliance with the international standards of series ISO 14040 [11], to assess the environmental impact throughout the product life cycle of a rotary compressor for an air-conditioner. We used the LCA method as this approach considers the full life cycle and it avoids problem shifting. Therefore, this prevents reducing the environmental burden in one stage whilst increasing the impacts at other stages of the life cycle. LCA is based on internationally accepted standards and is widely recognized as the best approach to quantify the environmental burden on the whole life cycle of a product. The details of the LCA method are described as following.

2.1 Goal and scope definition

2.1.1 Goal of the study

The goal of the present study was to: (1) evaluate the environmental impacts throughout the life cycle of the fixed speed rotary compressor produced in Thailand and

(2) identify hotspots and suggest the options to improve the environmental performance of the fixed speed rotary compressor toward an environmentally-friendly product.

2.1.2 Functional unit

A functional unit (FU) of this study was defined as the 12,000 BTU/h rotary compressor with HCFC22 (R22) refrigerant. Its life span was assumed for 5 years based on the compressor warranty. This compressor is used for household air conditioner systems. The main technical parameters are described in Table 1.

2.1.3 System boundary

The system boundary of the study is based on a cradle-to-gate and cradle-to-grave approach, as shown in Fig. 1. A cradle-to-gate approach is an assessment of a partial product life cycle from resource extraction to material production, product manufacturing, and all related transport. A cradle-to-grave is the full life cycle assessment covered from the resource extraction to material production, product manufacturing, usage, and disposal.

2.1.4 Assumption and limitation of the study

The foreground data from the two stages; material preparation and compressor manufacturing site-specific data were collected using questionnaires. However, the data came from manufacturers located in Thailand only. For the disposal stage, it was difficult to collect on-site data for the actual waste management system of the compressor in Thailand due to the lack of relevant law and system to support such activity. Thus, a disposal scenario had been created based on the management of the compressor disassembly plant. This yielded quantitative information concerning percentages of materials sale for recycling, landfill, and incineration, which were

Table 1 Technical parameters of a rotary compressor with R22 refrigerant

Parameter	Quantity	Unit
Type	Fixed speed single rotary	
Weight	15.9	kg
Rated power	1.14	kW
Frequency	50	Hz
Voltage	220–240	Volt
Refrigeration capacity	12,000	Btu/hr
Refrigerant	R22	
Compressor oil	520	cc

Fig. 1 System boundary of the study

used as input to calculate environmental burden. This was conducted using software and database provided within the program for each waste management technique. Table 2 shows the background and foreground systems as classified in this study.

2.2 Life cycle inventory

Once data from suppliers were collected, the energy and raw materials consumption, and emissions to the atmosphere, water, and land, were quantified for each process, and the mass balance in the processes are checked. The

Table 2 Background/foreground systems and data characteristics

Life cycle phase	Systems	Data sources	Data characteristics
Raw material production	Background	Ecoinvent databases [3]	Embodied environmental burden of raw materials
Electricity generation	Background	Ecoinvent databases [3]	Embodied environmental burden of Thai electricity grid mixed
Tab water production	Background	Thai life cycle inventory database [15]	Embodied environmental burden of tab water production in Thailand
Material preparation	Foreground	Site-specific data	The weighted average of two material companies in Thailand
Manufacturing	Foreground	Site-specific data	The weighted average of two compressor companies in Thailand
Use	Foreground	Assumption	Electricity use 1.14 kW, lifespan 5 years, the compressor operates 8 h/day, 365 days/year, and compressor running 70%
Disposal	Foreground	Prutichaiwiboon and Mungcharoen [20] and Harabut [8]	$E_{EoL} = \sum [(1 - R_{R,i}) \times E_{d,i}] + E_{tW}$ E_{EoL} = environmental burden of end-of-life stage $R_{R,i}$ = recycle rate of material type i (see Table 5) $E_{d,i}$ = environmental burden of final disposal of material type i E_{tW} = environmental burden of transport of end-used product

emissions related to the electricity were calculated based on the Thailand power grid including natural gas (69.23%), coal (19.72%), hydro power (7.62%), fuel oil (0.59%), diesel (0.11%), and renewable energy (2.73%) [5]. The inventory calculations were conducted using commercial LCA software.

2.2.1 Material production

The data for some material types, such as cast iron, copper, and high-grade steel parts, and the paint used in the compressor production was gathered from the material production companies in Thailand. On the other hand, the rest of the raw materials were imported from foreign countries. The detailed information on the inventory data for the fixed speed rotary compressor is shown in Fig. 2. The example of the main materials used for a fixed speed rotary compressor is silicon steel, hot-rolled steel sheet, cast iron, and copper with a composition of 47.10%, 22.26%, 15.07%, and 9.49%, respectively. Table A2, from the Electronic Supplementary Materials, shows the main input–output data needed to produce a fixed speed rotary compressor.

2.2.2 Manufacturing

The data for the compressor manufacturing stage, based on questionnaires and interviews, was collected from two compressor companies in Thailand during the production period in 2016. The process flow diagram is the basis for a mass balance check. Mass balance calculation of each unit process was performed for the aggregate of a group of processes, or for each unit process individually.

Compressor manufacturing processes were divided into four steps as following.

- (1) Core process: Rotors and stators were produced at this step. The stator was the part that produced electricity induction to generate a magnetic field that rotated the rotor.
- (2) Machining process: Mechanical mobile parts that moved together with the rotor and parts that compressed refrigerant pressure were produced at this step.
- (3) Press process: It produced the outer body and accumulator parts of the compressor.
- (4) Assembly process: Parts produced from the above processes were assembled to the rotary compressor at this point. The next procedures were leakage checking, painting, and nitrogen charging to prevent air permeating into the compressor. Finally, the products were packed into steel boxes for the export market and plywood boxes for domestic sales.

A process flow diagram of the compressor manufacturing stages is shown in Fig. 3. The main materials input of the rotary compressor production process is shown in Fig. 2. The production of one unit of a rotary compressor requires 10.17 kg of water, 19.59 kWh of electricity, and 0.37 kg of natural gas. The air emissions from natural gas combustion in the production process was calculated based on the emissions factor from the IPCC guidelines [10] and the EMEP/EEA guidebook [4]. Air emissions from fossil fuel combustion will be estimated as follow:

$$\text{Emission (kg/FU)} = (\text{energy use}_i(\text{TJ/FU}) \times \text{EF}_i(\text{kg pollutant/TJ})) \quad (1)$$

where EF_i represents the emissions factor of each energy type 'i' (kg pollutant/TJ), and subscript 'i' is the energy type such as LPG, natural gas, diesel, and fuel oil. Table A3 in the Electronic Supplementary Material shows the inventory data of a fixed speed rotary compressor manufacturing stage.

2.2.3 Transport

The rotary compressor transport was divided into two stages, oversea and domestic, as shown in Table 3. For oversea transportation, container ships were used for importing raw materials and exporting the rotary compressors. In a case of domestic transportation, trucks were the vehicles for sending raw materials between suppliers and manufacturers and between rotary compressor manufacturers to customers. The reference unit used for the transportation model in this study is tonne-kilometers (tkm), which refers to transporting one ton for one kilometer and simultaneously takes the traffic volume and mileage into consideration. The air emissions of the transportation model used in this paper is shown as Eq. (2) below.

Fig. 2 Material composition of the fixed speed rotary compressors

Fig. 3 Production process of a rotary compressor

Table 3 Transport of the raw materials and the rotary compressor

Materials/product	Oversea		Domestic	
	Distance (km)	Vehicle	Distance (km)	Vehicle
<i>Materials</i>				
Steel sheet	4500	Container ship	64	Tuck
Silicon steel	4500	Container ship	64	Tuck
High grade steel	4500	Container ship	10	Tuck
Cast iron	–	–	180	Tuck
Sintered steel	2100	Container ship	22	Tuck
Copper wire	–	–	112	Tuck
Copper tube	–	–	390	Tuck
Aluminum ingot	6200	Container ship	22	Tuck
<i>Product</i>				
Rotary compressor	–	–	104	Tuck

$$Emission_T = \sum_i (AD_i \times EF_i) \quad (2)$$

where $Emission_T$ is the air emission of transportation stage per FU, AD_i is Activity data for item i , and EF_i is emission factor for item i .

2.2.4 Usage

In the use stage of a rotary compressor, power consumption is an important factor to be considered. The refrigerant R22, used in the cooling system for a fixed speed rotary compressor model, was included in this stage. The R22 is a single hydrochlorofluorocarbon (HCFC) compound. It has low chlorine content and ozone depletion potential is 0.05 kg CFC11 eq. per kg R22 and is only a modest global warming potential at 1810 kg CO₂ eq. per kg R22 [14]. In this study, the use stage is assumed that the product's life span was 5 years based on compressor warranty and operated for 8 h a day and 365 days a year. The power consumption rate was 1.14 kW, the compressor was on the running only 70% [20] of the total operating time, i.e. 5.6 h/day for operating of the compressor and other the compressor off. The refrigerant was 1100 cc. of R22 and it was assumed there was no leakage over 5 years. Thus, electricity consumption of a fixed speed rotary compressor can be calculated as follow:

$$\begin{aligned} \text{Electricity consumption} &= 1.14 \text{ kW} \times 8 \text{ h} \times 365 \text{ days/year} \times 5 \text{ year} \times 0.70 \\ &= 11,650.80 \text{ kWh.} \end{aligned}$$

Table A4 from Electronic Supplementary Material shows the inventory data of the use stage of a rotary compressor.

2.2.5 Disposal

As mentioned earlier that, due to the lack of completed on-site data, the disposal stage is assumed to be a scenario based on the management of the end-user product being disposed of compressor disassembly plants [8, 20]. Table 4 shows the percentages of the materials in the

Table 4 Disposal scenario data. Source: Prutichaiwiboon and Mungcharoen [20] and Harabut [8]

Materials	Recycle (%)	Landfill (%)	Incineration (%)
Steel	95	5	0
Cast iron	88	12	0
Copper	94	6	0
Aluminum	60	40	0
Lubricant oil	0	20	80

compressor under this scenario as subjected to three types of treatment: recycling, landfill, and incineration. The R22 refrigerant evaporates into the atmosphere, but it was not collected due to the lack of knowledge and technology for recycling in Thailand. The air emission of end-of-life stage model used in this paper is shown as Eq. (3) below.

$$E_{EoL} = S[(1 - R_{R,i}) \times E_{d,i}] + E_{TW} \quad (3)$$

where E_{EoL} is the environmental burden of end-of-life stage, $R_{R,i}$ is the recycled rate of material type i (see Table 4), $E_{d,i}$ is an environmental burden of final disposal of material type i , and E_{TW} is the environmental burden of the transport of end-used product.

2.3 Life cycle impact assessment

Life cycle impact assessment was divided into classification and characterization. In the classification step, all substances obtained from the inventory analysis were sorted into classes according to the effect they had on the environment. In the characterization step, attempts to assess the contribution of the assigned input/output data to the respective impact category to result finally in an impact profile were made. Both classification and characterization

steps were performed in this study, however, the normalization and weighting steps were not included because these steps were rather subjective and required the use of normalization and appropriate weighting factors.

To assess the environmental impacts in this study, the ReCiPe midpoint (H) V1.13 method provided within SimaPro software was employed. The impact categories selected in the study are climate change (CC), ozone layer depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF), water depletion (WD), metal depletion (MD), and fossil depletion (FD). The equation to calculate an indicator result of impact category i is follows:

$$I_i = \sum_{j=1}^m C_{ij} x_j \quad (4)$$

where I_i is an indicator result of impact category i , C_{ij} is the characterisation factor for intervention j within impact category i , and x_j is an amount of intervention (emission, resource extractions or water use) j .

3 Results and discussions

3.1 Life cycle inventory analysis

From the inventory analysis result, environmental parameters had been set for over 1000 items. Some environmental parameters of the fixed speed rotary compressor were selected based on the analysis above and are summarized in Table 5. The energy-related resources in the use stage; like coal, crude oil, and natural gas, is the most of important contributor. The production of raw materials contributed to the use of iron ore, and copper because these are the main materials used in the rotary compressor production. The negative contribution at the disposal stage is due to environmental credit from metal recycling.

Table 5 showed contributions to the air emissions in each use stage, which resulted from the electricity used. It was obvious that the electricity consumed during the use stage contributed the most to the total emissions of CO₂, SO₂, and NO_x. These substances have been known as major contributors to global warming and acidification whereas the emission from R22 in the disposal stage has a direct impact on the ozone depletion and also contributes to the global warming potential. It should be noted that the amounts of resources, air emissions and water emissions shown in the disposal stage were negative values. This was due to the recycling scenario used which had a positive impact on the environment. The R22 emissions in the disposal stage were released from the refrigerant in the compressor disassembly plant. The inventory data were further used to evaluate the impact assessment in the next section.

3.2 Impact assessment result

3.2.1 Life cycle result of cradle-to-gate stage

Based on the ReCiPe midpoint method, we selected the ten environmental impact categories including CC (kg CO₂ eq.), OD (kg CFC-11 eq.), TA (kg SO₂ eq.), FE (kg P eq.), HT (kg 1,4-DB eq.), POF (kg NMVOC), PMF (kg PM10 eq.), WD (m³), MD (kg Fe eq.), and FD (kg oil eq.). Figure 4 illustrated the results of the environmental impact assessment obtained from the ReCiPe midpoint method for all 10 categories, employing the cradle-to-gate approach including the raw materials production, materials transport, and manufacturing stages.

Based on the cradle-to-gate approach, all environmental impact categories in the raw material production stage contributed a large portion of the compressor

production, as shown in Fig. 4 and Table 6. It is presumed to be due to the fact that much energy is consumed in the raw material production stage and consequently, large emissions are generated. In addition, raw material production influences a significant amount of OD, TA, FE, HT, PMF, and MD that predominates more than 90% of the compressor production. The HT spectacle is attributed to the significant amounts of As, Pb and CN generated during copper production. The MD category is ascribed to the important volume of iron ore and copper consumed during produced the steel and copper. The copper part of production leads much TA, FE, PMF, POF, and OD due to the large amount of SO₂, phosphorous, dust, NMVOCs and CFCs generated from copper production, even though the mass is substantially less than that of the steel part. Steel production uses a lot of energy and produces robust environmental impacts because of the high mass demand for this material (Fig. 2). By contrast, aluminum production consumes little energy and generates few emissions due to the small composition of materials used in the production. Furthermore, cast iron production influences less HT, FE, and OD than other materials due to the process generating fewer heavy metals, phosphorous, and CFCs.

The compressor manufacturing stage influences more important environmental impacts than raw materials transportation due to the enhanced electricity consumption of the metal part preparation during the manufacturing processes (Fig. 4 and Table 6). In addition, this stage emits pollutions associated with CC, OD, TA, FE, HT, POF, PMF, WD, and FD from the fossil fuels combustion in power plants. The MD level is much lower in the manufacturing stage than in the other stages due to no metal ore being used in this stage.

3.2.2 Life cycle result of cradle-to-grave stage

Figure 5 presents the results of the environmental impact assessment obtained from the ReCiPe midpoint method for all 10 categories and all five phases, throughout the product's life cycle. As seen in Fig. 5, the environmental impacts in nearly all categories came from the use stage, except for the OD and MD impact categories. Raw materials contributed to the most environmental impact categories due to metal depletion (MD). The disposal stage contributed the lowest impacts to the environment, possibly due to the high percentage of recycling applied to the disposal scenario, which resulted in a negative score in the metal depletion categories. This implied that recycling could reduce the impacts of disposal and resource depletion.

Figure 5 and Table 7 demonstrate that the use stage has the highest energy demand with these demands

Table 5 Life cycle inventory analysis of the fixed speed rotary compressor. Source: Analyzed the inventory result by using the SimaPro 8.0

Inventory	Substances	Raw material production				Materials transport	Components manufacturing	Compressor transport	Use	End-of-life
		Steel	Cast iron	Copper	Others					
Resources (kg)	Copper	2.72E-02	1.20E-04	1.77E-01	6.49E-02	1.81E-07	9.00E-06	9.87E-08	5.17E-02	-7.28E-05
	Iron	3.14E+00	2.65E+00	1.02E-02	1.91E-02	2.76E-05	1.16E-03	0.00E+00	8.20E-01	-1.64E+01
	Coal	5.34E+00	1.87E+00	5.22E-01	1.65E+00	4.63E-03	3.76E+00	1.99E-07	2.65E+03	-5.43E+00
	Crude oil	7.10E-01	1.90E-01	5.68E-02	9.78E-01	1.63E-01	1.42E-01	5.22E-02	7.16E+01	-6.66E-01
	Natural gas	8.16E-01	1.34E-01	2.09E-01	1.46E-01	4.34E-03	2.13E+00	2.25E-03	1.26E+03	1.39E+00
	CO	1.24E-01	7.81E-02	0.00E+00	1.73E-02	1.16E-03	3.11E-03	5.50E-04	3.04E+00	-4.21E-01
	CO ₂	1.41E+01	4.65E+00	1.30E+00	4.44E+00	4.97E-01	1.31E+01	1.76E-01	8.55E+03	-1.05E+01
	SO ₂	4.82E-02	1.46E-02	5.19E-03	4.62E-02	7.24E-03	3.13E-02	4.47E-05	2.20E+01	-3.13E-02
	NO _x	3.62E-02	1.09E-02	3.11E-03	1.51E-02	7.89E-03	1.81E-02	1.70E-03	1.08E+01	-3.24E-02
	CH ₄	4.95E-02	1.74E-02	2.78E-03	2.40E-02	2.70E-04	2.29E-02	4.96E-05	1.73E+01	-6.09E-02
Air emission (kg)	N ₂ O	3.73E-04	7.80E-05	5.72E-05	1.73E-04	1.24E-05	3.20E-04	1.61E-07	2.22E-01	4.94E-05
	H ₂ S	9.13E-05	5.41E-05	2.04E-05	4.19E-06	4.34E-08	9.11E-05	0.00E+00	6.44E-02	-2.58E-04
	HCl	1.50E-03	3.51E-04	1.14E-04	8.59E-04	1.02E-05	7.09E-04	0.00E+00	5.01E-01	-3.70E-04
	CFCs	1.23E-08	1.25E-09	5.76E-08	4.68E-07	1.11E-11	5.72E-11	0.00E+00	4.05E-08	-7.76E-10
	HCFC-22	2.07E-06	1.48E-06	1.11E-08	8.46E-07	2.64E-10	1.39E-08	0.00E+00	9.82E-06	1.11E+00
	PM	6.83E-02	3.00E-02	4.07E-03	1.58E-02	7.53E-04	5.91E-03	1.24E-04	4.18E+00	-1.47E-01
	BOD	2.52E-02	7.51E-03	3.62E-06	1.28E-02	1.62E-03	3.62E-03	1.18E-06	1.08E+00	-2.46E-02
	COD	4.18E-02	1.29E-02	6.13E-04	1.65E-02	1.63E-03	3.43E-02	4.50E-07	1.33E+00	-5.61E-02
	NH ₄	5.89E-05	1.67E-05	0.00E+00	4.36E-05	4.02E-07	3.45E-05	0.00E+00	2.44E-02	-4.82E-05
	Hg	2.50E-06	4.99E-07	3.35E-09	4.89E-07	1.26E-09	1.64E-06	7.40E-14	1.16E-03	-3.32E-07
Water emission (kg)	Cr	3.25E-06	1.71E-07	6.14E-07	1.35E-06	2.84E-08	1.32E-06	2.13E-12	1.17E-03	1.13E-06
	Pb	1.52E-04	1.97E-05	3.20E-07	8.75E-05	5.47E-08	4.91E-06	0.00E+00	3.47E-03	-4.18E-05
	As	1.70E-04	1.92E-05	0.00E+00	1.80E-04	2.03E-08	2.05E-05	7.09E-13	1.45E-02	-1.26E-05
	CN-	4.32E-05	9.08E-06	1.28E-07	2.29E-05	1.96E-08	1.54E-08	0.00E+00	1.09E-05	-1.25E-05

Fig. 4 Characterization results of the environmental performance of the compressor production

accounting for more than 95% of the total portion in the whole life cycle almost categories. This result is ascribed to the high electricity consumption. Moreover, the compressor use stage is carried out with the highest TA (97.38% of the whole life cycle) emitting a huge amount of SO_2 and NO_x during electricity generation. CC performs 80.67% of the total part due to a significant amount of CO_2 , CH_4 , and N_2O emissions being generated. As with CC and TA, this stage makes the most FE and HT (96.51% and 89.41% of the whole life cycle, respectively) due to the large quantities of NH_4 , NO_x and heavy metal generated during fossil fuel combustion in power production. The use stage of compressor is likewise prominent in the results acquired regarding POF and PMF impacts and reports for 98.39 and 97.10% of the total share in the whole life cycle, respectively. This discovery is the reason for the truth the electricity generation emits large amounts of CH_4 and particulate matters. In addition, the compressor use stage is dominates the effects achieved by finding WD and FD impacts due to water and fossil fuel consumption in electricity production. Nevertheless, the use stage results in less MD than material production (especially steel and copper production) due to fewer metals being consumed during compressor use. In addition, in the disposal stage, it was found that the disposal of refrigerants was the greatest contributor to the OD impact. The results shown in Fig. 5 indicate the main causes of the environmental impact in each stage of the whole life cycle. These data could be efficiently used as guidelines for environmental management to reduce the environmental impact of a fixed speed rotary compressor in the key hot spots [9, 12, 16, 23]. A similar study in Brazil [27] reported most impact categories came from the use stage of the compressor,

while our study showed a more similar trend to a study in China [23] except for in the ozone depletion and metal depletion categories.

3.3 Sensitivity analysis result

A sensitivity analysis refers to an estimation of the magnitude of influence the input parameters have on the LCA results. The compressor is the main part of the air conditioner and a common impact for electric products is the electricity consumption. However, the electricity consumption of the air conditioner depends on several factors such as the cooling time or inoperative period, outside temperature, users' setting of inside temperature, and the energy efficiency of the appliance.

In this study we investigated the influences of inside temperature set by the user on the LCA outcome. The variation of inside temperature is examined in the range from 22 to 27 °C. The electrical power input for air cooling at a preferred temperature was calculated based on Eq. (5) [21].

$$P_{\text{input}} = \frac{P_{\text{output}}}{0.1 \times \left(\frac{T_{\text{inside}}}{T_{\text{outside}} - T_{\text{inside}}} \right)} \quad (5)$$

where P_{input} is the actual power input (kW), P_{output} is the cooling capacity output (kW), T_{outside} is the outside temperature and T_{inside} is the preferred inside temperature. For the calculation, temperatures are transformed to absolute values in units of degrees Kelvin. During cooling, the compressor system was assumed to be operating with a 70% loading [20]. In 2019, the mean daily maximum outside

Table 6 Detailed environmental impact distribution of the fixed speed rotary compressor based on cradle-to-gate approach

	Raw materials				Material transport			Manufacturing			Total		
	Steel	Cast iron	Copper	Aluminum	Other	Chemical	Oversea	Domestic	Electricity	Fuels		Water	Process emission
CC	2.47E+01	5.08E+00	1.35E+01	3.51E+00	9.01E-01	7.21E-01	5.00E-01	7.02E-03	1.21E+01	1.04E-01	7.16E-03	9.30E-01	6.21E+01
DLD	1.39E-06	2.49E-07	1.33E-05	6.07E-08	7.49E-07	4.89E-07	9.40E-08	0.00E+00	3.16E-07	0.00E+00	0.00E+00	0.00E+00	1.66E-05
TA	1.08E-01	2.11E-02	5.66E-01	1.84E-02	3.34E-02	4.76E-03	1.18E-02	4.23E-05	3.97E-02	7.75E-05	2.42E-05	1.77E-03	8.06E-01
FE	2.20E-02	1.75E-03	1.37E-01	5.28E-04	7.82E-03	1.23E-04	5.07E-06	0.00E+00	6.87E-03	0.00E+00	0.00E+00	0.00E+00	1.76E-01
HT	3.53E+01	5.27E+00	3.03E+02	6.87E-01	1.74E+01	1.14E-01	1.30E-02	2.30E-06	4.35E+00	4.39E-04	3.12E-06	4.35E-05	3.66E+02
POF	1.06E-01	2.18E-02	1.40E-01	1.02E-02	8.77E-03	8.29E-03	9.00E-03	7.99E-05	2.11E-02	8.07E-05	2.59E-05	3.05E-03	3.29E-01
PMF	1.04E-01	2.09E-02	1.78E-01	7.66E-03	1.07E-02	1.81E-03	3.64E-03	1.60E-05	1.22E-02	2.38E-05	7.34E-06	7.41E-04	3.40E-01
WD	2.69E-01	2.39E-02	2.31E-01	5.45E-03	1.49E-02	8.48E-03	7.44E-04	0.00E+00	8.85E-02	0.00E+00	0.00E+00	0.00E+00	6.42E-01
MD	4.73E+01	2.71E+00	5.59E+01	2.04E-02	3.23E+00	1.23E-03	6.59E-05	2.65E-08	2.05E-03	3.76E-07	7.82E-06	0.00E+00	1.09E+02
FD	5.77E+00	1.17E+00	4.05E+00	6.62E-01	2.65E-01	9.96E-01	1.75E-01	2.23E-03	3.65E+00	3.00E-02	1.11E-02	0.00E+00	1.68E+01

temperature in Thailand was 35.58 °C [24]. Table A5 in the Electronic Supplementary Material shows the inventory data of the sensitivity analysis in the use stage of the compressor.

As expected for electrical equipment, the use stage contributed the majority of the total life cycle impact in almost categories. For the climate change impact, the total use stage accounted for 80% of the entire life cycle, the mean output CC impact was 10,302 kg CO₂-eq per FU, inducing a range of 12,200 kg CO₂-eq during the 5th and 95th percentile in the distribution of results, as shown in Fig. 6. The variation range of indoor temperature settings by users resulted in a mean life cycle climate change that varied from 8845 to 12,927 kg CO₂-eq. The mean climate change impact was significantly different for different temperature settings. Setting an inside temperature of 27 °C lowered the total CC by 31.58% when compared with 22 °C. For each, a 1 °C increase in the inside temperature setting reduced the total CC emissions by 6.37%. The coefficient of variation of the estimated CC distribution was narrower with an increasing inside temperature setting. Details of CC emissions for different inside temperature settings are shown in Table 8.

3.4 Improvement options toward environmentally-friendly product

From the life cycle assessment of the fixed speed rotary compressor performed in the present study, the highest environmental impact occurred in the use stage. This was because of the intensive consumption of energy in the 5-year period, which was about 11,650 kWh. The disposal stage of the refrigerant represented the main climate change impact. To solve the disposal problems, it was necessary to increase the recovery rate and disposal suitably. Therefore, the main idea to solve the environmental problem was to improve the fixed speed rotary compressor in terms of energy efficiency, such that the input power would be decreased while maintaining the same cooling capacity. This might be achieved through several approaches as follows; developing the new types of the compressor such as the twin rotary compressor that uses an inverter system to control the operation, and uses alternative refrigerants. For the inverter twin rotary compressor, the use of energy could be reduced by approximately 20–30% [25], equivalent to reducing 1700–2500 kg CO₂ eq. In the raw material production stage, enamel copper wire was the component that produced the highest impact and was the most difficult to be replaced by other materials. Nowadays the development of high energy efficient copper wire components, such as superconductors, that could reduce energy loss and the impact of materials in the conducting component.

Fig. 5 Characterization results of the environmental performance of the entire life cycle

Table 7 Environmental impact distribution of the fixed speed rotary compressor based on cradle-to-grave approach

	Raw materials	Raw material transport	Manufacturing	Compressor transport	Use	Disposal	Total
CC	4.84E+01	5.07E−01	1.32E+01	1.78E−01	8.59E+03	2.00E+03	1.07E+04
OLD	1.62E−05	9.40E−08	3.16E−07	0.00E+00	2.23E−04	5.55E−02	5.57E−02
TA	7.52E−01	1.18E−02	4.16E−02	1.03E−03	2.81E+01	−5.17E−02	2.88E+01
FE	1.69E−01	5.07E−06	6.87E−03	0.00E+00	4.85E+00	−6.65E−04	5.03E+00
HT	3.62E+02	1.30E−02	4.35E+00	5.63E−05	3.08E+03	−1.98E+00	3.44E+03
POF	2.96E−01	9.08E−03	2.42E−02	2.01E−03	1.49E+01	−8.79E−02	1.51E+01
PMF	3.24E−01	3.65E−03	1.29E−02	5.14E−04	8.60E+00	−8.42E−02	8.86E+00
WD	5.53E−01	7.44E−04	8.85E−02	0.00E+00	6.25E+01	3.62E−02	6.32E+01
MD	1.09E+02	6.60E−05	2.06E−03	6.46E−07	1.45E+00	−1.65E+01	9.41E+01
FD	1.29E+01	1.77E−01	3.69E+00	5.43E−02	2.58E+03	−1.62E+00	2.59E+03

Fig. 6 Histogram depicting the distribution of output total climate change impact arising from variation in the setting of inside temperature in the use stage of the compressor

Table 8 Breakdown of estimated overall climate change impact associated with scenarios running the compressor at different temperatures setting; mean, standard deviation (SD), standard error (SE), and coefficient of variation (CV)

Temperature setting (°C)	Climate change impact (kg CO ₂ -eq)			
	Mean	SD	SE	CV
22	12,927	935	7.23	0.30
23	12,103	920	7.61	0.29
24	11,268	812	7.20	0.26
25	10,477	790	7.54	0.25
26	9673	780	7.03	0.21
27	8844	599	6.78	0.19

Alternative scenarios for improving the energy efficiency of the rotary compressor were investigated in this study as follows.

Option A: a shift from a fixed speed rotary compressor to the inverter twin rotary compressor with R410A refrigerants used in the cooling system, but 0% of the R410A refrigerant is recovered from the waste product.

Option B: a shift from a fixed speed rotary compressor to the inverter twin rotary compressor with the R410A refrigerants used in the cooling system and 50% of the R410A refrigerant being recovered and treated by the combustion process.

Option C: a shift from a fixed speed rotary compressor to the inverter twin rotary compressor with R32 refrigerants used in the cooling system.

The main materials used for the inverter twin rotary compressor are silicon steel (38.57%), hot-rolled steel sheet (32.71%), cast iron (16.36%), and copper (7.17%). The usage conditions of these scenarios are presented in Table A4 (see supplementary materials). The electricity consumption of the inverter twin rotary compressor can be calculated using Eq. (6).

$$EC = \frac{C \times h \times d \times y}{SEER \times 1000} \quad (6)$$

where EC is the electricity consumption (kWh), C is the cooling capacity (Btu/h), h is an average operating time per day (h/day), d is the operating day per year (day/year), y is the service life of compressor (year), and $SEER$ is the seasonal energy efficiency ratio (Btu/h/W).

Based on the three improvement options shown in Fig. 7, the comparison of the LCA characterization impact category of each option resulted in a reduction from the base case scenario. The use of the inverter twin rotary compressor with R32 refrigerant (option C) was the best option and resulted in a 38% CC impact reduction compared to base case, whereas options A and B would

Fig. 7 Comparison of the environmental impact of the improvement options of the compressor

reduce the CC impact by 22% and 30%, respectively. In the disposal stage, if 50% of the R410A refrigerants could be recovered and combustion treated (Option B), the CC impact could be reduced by 762 kg CO₂ eq. or 10% of the entire life cycle. In terms of ozone depletion impacts, all three options have resulted in the termination of ozone layer depletion. In other impact categories, option C produced a reduction of 29–53% compared to the base case, while options A and B reduced this impact by 22–53% and 22–44%, respectively.

4 Conclusions

From the life cycle assessment of a fixed speed rotary compressor, the software SimaPro 8.0 with the ReCiPe midpoint (H) V1.13 method, found the use stage provided the highest environmental impact because of the use of electricity throughout the compressor's life. To reduce the impact, the compressor should be improved so that it has higher energy efficiency. The inverter twin rotary compressor with environmental-friendly refrigerants such as R32 is the best option in order to reduce the environmental impact from the compressor usage. In addition, the steel parts and copper wire have the most important effect in the raw material production stage. Other hot spots identified in this study were the machining process and disposal of refrigerants. The study also provided a quantitative indicator concerning the major sources of the environmental impact and eco-design options for improving the energy efficiency of compressor to be more environmentally friendly products.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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