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Environmental evaluation of pump replacement period in water supply systems of buildings

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Abstract

Cost analysis of facility replacement is the common method used in building services facility management nowadays, however, replacement evaluation from the environmental aspect still lacks in literature. This study is the first trial to introduce the environmental evaluation, life cycle assessment technique is adopted, into the replacement period justification of building services facilities, taking water supply pump in buildings as an example. An environmental evaluation model of water supply pump replacement is proposed in this study to minimize the total environmental impact (i.e. energy consumption) of the water supply system, which compares the extra operational energy expenditure in the long-term operation to the pump embodied energy. The literature review is used to obtain the energy intensity data, of mining, metal production, and metal casting, for the determination of pump embodied energy. The results demonstrate that for common pump motor ratings of 1.1–5 kW in water supply systems of buildings, with annual efficiency drop and pump energy intensity that ranges from 0.012 to 0.028 and 18.2 to 177.6 GJ/t iron and steel respectively, a longer pump replacement period is noticed at the greater energy intensity of pump (the maximum difference of the replacement period can be about 10 years). Besides, higher annual efficiency drop justifies a shorter pump replacement period. It was found that the replacement periods of smaller pumps are more sensitive to the pump energy intensity and annual efficiency drop. Moreover, it was also shown that for pumps with the maximum embodied energy intensity (i.e. 177.6 GJ/t iron and steel), for example, the pump material is stainless steel, the pump replacement periods evaluated on the environmental and economic grounds are comparable. The study results provide an alternative solution of pump replacement period for water supply systems in buildings based on the life cycle environmental assessment of water pump.

Keywords

Pump replacement period, life cycle assessment, embodied energy, water supply system, sustainable development

1. Introduction

Climate change is one of the major challenges of our time [1]. To combat climate change and in response to the Paris Agreement, Hong Kong has set a carbon intensity reduction target of 65% to 70% by 2030 using 2005 as the base, which is equivalent to 26% to 36% absolute reduction and a reduction to 3.3-3.8 tonnes on a per capita basis [2]. To achieve this goal, it needs the effort of each sector in the whole society, which means that each sector in the society should establish its carbon reduction target. In Hong Kong, buildings account for about 90% of the city's electricity usage and over 60% of the carbon emissions are attributable to generating electricity for buildings [2]. For the residential sector, air conditioning and hot water (e.g. showering and tap water use) are major energy-consuming end-uses and account for 26% and 24% respectively of the total energy demand in buildings of Hong Kong [3]. There is great potential to reduce carbon emissions by improving energy efficiency in buildings. Several construction practices and technologies, such as the increase of the building tightness and envelope insulation, and Low-E window, have been widely promoted and adopted in Hong Kong to reduce the energy consumption of air conditioning in buildings. The energy consumption of hot water use in buildings includes the energy consumptions for plumbing the water into the flat and heating the water, in which wastewater heat recovery by specifically designed heat exchanger has been proposed in the previous study to reduce the energy consumption for heating water [4]. However, energy efficiency improvement of building water supply system is less concerned, and related researches are limited in the literature.

It was reported that 2-3% of worldwide electricity was consumed for pumping water in water supply systems [5]. Similar results revealed that the energy demand of the water supply system accounts for 1-4% of the total electricity and is the largest energy consumer in a city [6]. In Hong Kong, water supply systems in buildings account for 1.6% of the overall electricity consumption of the city, and in which 40% of the total pumping energy is consumed inside buildings [7]. As the energy consumption by building water supply systems accounts for a large portion, improving the energy efficiency of the water supply system is one of the key aspects to achieve building sustainable development. Studies revealed that the energy efficiency of water supply systems for high-rise buildings is under 0.25 and that over 75% of the energy input is wasted [8]. Several aspects to improve the total energy efficiency of building water supply system have been investigated in our previous studies, including the optimization of design flow rate corresponding to the instantaneous water demand and adoption of low flow appliances [9], relocation of the water tank, e.g. adoption of the intermediate tank in high-rise buildings water systems [10].

Arpke and Hutzler [11] claimed that about 85% of electrical energy was consumed to pump water in the whole cycle of the water supply. Gomes [12] also indicated that 80-90% of the energy consumed for pumping water in water supply systems is used by motor-pump sets. Previous studies revealed that about 50% of the energy loss in the water supply system is caused by the pump [8, 13]. It can be seen that water pump contributes to the major energy consumption as well as energy loss in water supply systems. Aged, poorly maintained and mismatched water pumps operating at low efficiency are highly undesired. Wong et al.'s study [14] on water supply pumps in 20 systems of Hong Kong buildings showed that pump efficiency drops 1.5% per year of installation on average. Kaya et al. [13] indicated that the selection of a proper pump could curtail the energy consumption of the pump by 30%. Vilanova and Balestieri's [15] review study showed that 2-25% of the energy can be saved with correct pump sizing or by substituting installed pumps with the most efficient pumps or by operating pumps at the most efficient operating point. These studies [13-15] indicate that replacement of aged or mismatched pumps with new and high-efficiency pumps will reduce the operation energy consumption of the water supply system. However, additional energy consumption, as well as energy-related carbon emission, will be caused which are embodied in the new pump manufacturing. Cost analysis of facility replacement is the common method used in building facility management [16, 17], and optimization of water pump replacement based on the economic justification has been studied in our previous work [18]. Environmental evaluation of building structures, e.g. green walls and roofs, from the aspects of energy consumption and carbon emission has been conducted [19, 20], however, the environmental evaluation of building services facilities still lacks in literature.

Life cycle assessment (LCA) is a powerful tool for addressing the environmental aspects and potential environmental impacts of a product, process, or activity throughout its life cycle from raw material acquisition to final disposal (i.e. cradle-to-grave) [21]. It involves the compilation and quantification of inputs and outputs for a product system and the evaluation of the magnitude and significance of the potential environmental impacts throughout the life cycle of the product [21, 22]. LCA technique has been used to assess the environmental impact of some production processes, such as mining and metal production [23, 24], and it is applied in this study to evaluate the pump replacement period. This study is the first trial to introduce the environmental evaluation into replacement period justification of building services facilities, taking water pump as an example, to minimize the total environmental impact of the water supply system. In this study, the environmental impact of the water supply pump in the environmental evaluation is represented by the energy consumption of the water supply pump in the life cycle.

2. Methodology

From the environmental aspect, pump replacement is suggested to minimize the total environmental impact (e.g. energy consumption) of water supply systems in the life cycle and is influenced by components like the initial energy consumption for manufacturing the pump (i.e. pump embodied energy), operational energy consumption, as well as the energy consumption of pump recycling and disposal. As the energy consumption of pump recycling and disposal accounts for a relatively small portion of the total energy consumption of water supply system in the life cycle and further the solid data of energy consumption of pump recycling and disposal is limited in literature, the energy consumption of pump recycling and disposal is not considered for the environmental evaluation of pump replacement in this study. An environmental evaluation model is proposed for the pump replacement, as shown in Eq. (1); the pump replacement period is suggested to be determined by comparing the accumulated extra energy expenditure at time t_s (year) (the left side of the equation) with the pump embodied energy $E_{embodied}$ (the right side of the equation), where $E_{pump,i}$ and $E_{pump,1}$ is the operational energy consumption by the pump in the i-th and first year of service respectively, t_s is the year of pump services. Comparing with the operational energy consumption of the pump in the first year of service, the extra energy consumption of pump operation ($E_{pump,i} - E_{pump,1}$) is caused by the drop of pump efficiency with operation time, which is probably due to corrosion, scaling of the impeller, casing, and other parts of pumps.

$$\sum_{i=1}^{t_s}\left(E_{pump,i} - E_{pump,1}\right) \geq E_{embodied}\ ; i = 1, 2, 3, \ldots, t_s \tag{1}$$

The yearly energy consumption of pump operation E_{pump} (kWh) is found related to the pump motor rating W_m (kW), which is given by Eq. (2), where $\eta_{c,1}$ is the overall pump efficiency at the first year of installation, $\eta_{c,t}$ is the overall pump efficiency in the t-th year of operation [14]. The overall pump efficiency η_c is defined as the product of pump efficiency η_p (50-80 %), mechanical transmission efficiency η_m (90-100%) that illustrating the power transmission between the motor and pump, and the electric motor efficiency η_e (70-96%), as shown in Eq. (3) [8, 13]. The pump efficiency η_p is determined by the ratio of useful hydraulic power delivered to the fluid P_e to the power input at the drive shaft P, as described in Eq. (4) [25], where ρ is the fluid density, g is the gravitational constant, Q is the flow rate of the pump, and H is the head of the pump.

$$E_{pump} = 450\frac{\eta_{c,1}}{\eta_{c,t}}{W_m}^{1.27} \tag{2}$$

$$\eta_c = \eta_p\eta_m\eta_e \tag{3}$$

$$\eta_e = \frac{P_e}{P}\ ;\ P_e = \rho g Q H \tag{4}$$

Considering the pump performance deterioration, the overall pump efficiency $\eta_{c,t}$ in the t-th year of operation is expressed as Eq. (5), where η' (year^{-1}) is the annual drop in the overall pump efficiency, t_s is the year of pump services [14]. According to Wong et al.'s study [14], the annual drop of overall pump efficiency for the best-case, average-case, and worst-case scenarios is 0.012, 0.015, and 0.028 respectively; the best scenario means the annual drop of overall pump efficiency is the least, while the worst scenario is with the greatest annual drop of overall pump efficiency.

$$\eta_{c,t} = \eta_{c,1} - \eta' t_s \tag{5}$$

In this study, the pump embodied energy is defined as the cumulative energy consumption for the pump manufacturing, including the energy consumption in the processes from raw material extraction (mining), metal production to pump manufacture. The pump embodied energy $E_{embodied}$ is expressed by pump weight m_{pump} and energy intensity of pump $e_{embodied}$, as shown by Eq. (6), where e_{mining}, e_{metal} and $e_{manufacture}$ are energy intensity in mining, metal production, and pump manufacture respectively, C_1, C_2, C_3 are coefficients which respectively represent the weight of materials (e.g. iron ore, metal) needed during the processes of mining, meal production and pump manufacture for one unit of pump weight. m_{mining} is the weight of ore needed during the mining process for manufacturing a pump, m_{metal} and $m_{manufacture}$ are the weights of metals needed during the processes of metal production and pump manufacture respectively for manufacturing a pump. The values of e_{mining}, e_{metal} and $e_{manufacture}$ are determined based on the review of the data in the literature, and details are described in the following section.

$$E_{embodied} = m_{pump}e_{embodied} = m_{pump}\left(C_1 e_{mining} + C_2 e_{metal} + C_3 e_{manufacture}\right)$$
$$C_1 = \frac{m_{mining}}{m_{pump}},\ C_2 = \frac{m_{metal}}{m_{pump}},\ C_3 = \frac{m_{manufacture}}{m_{pump}} \tag{6}$$

Pump manufacture commonly involves a great number of complex processes, and the process varies with the pump requirement and manufacturing factory. For reasons of confidentiality, the data of pump manufacture is rarely published. As casting pump body (casing) in the foundry is one of the main processes of pump manufacture, accounting for a great percentage of total energy consumption for pump manufacture, and some data about metal casting is available publicly. Considering the feasibility, in this study, the energy consumption in pump manufacturing processes is simplified to be represented by the energy consumption in metal casting. Although metal casting can not reflect the energy consumption in the whole process of pump manufacture, it is still meaningful to some extent for the first trial study in this area.

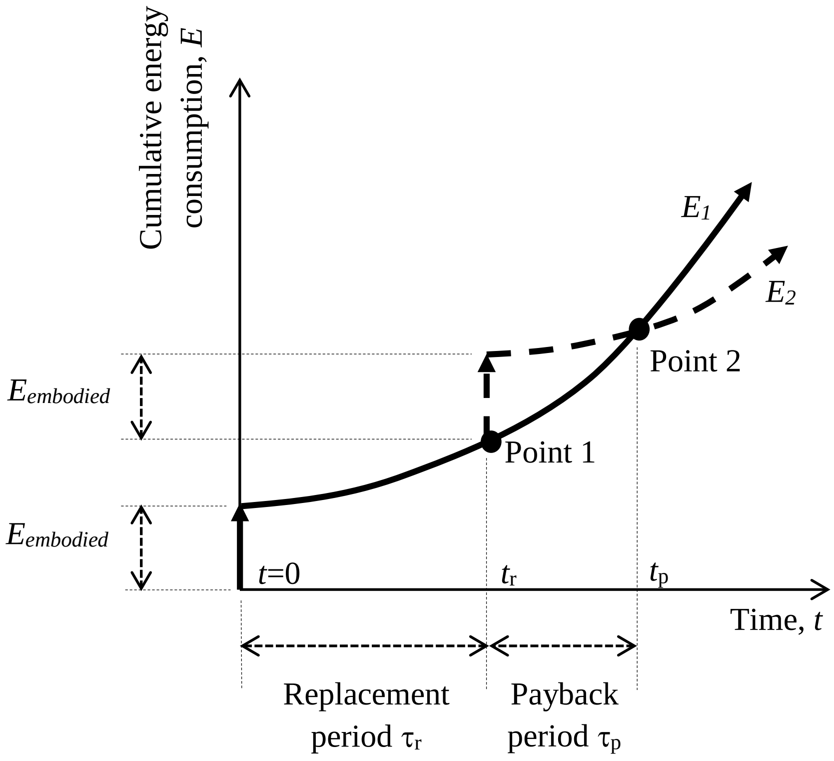
Centrifugal water pumps are common installations for freshwater pumps and flushing water pumps in buildings [26]. As suggested by the local government [26], the materials of construction of the pumps in buildings are summarized in Table A of Appendix A, including ferrous materials of stainless steel and cast iron, and non-ferrous materials of bronze and gunmetal. As the proportional share of the non-ferrous materials in the pump weight varies with pumps and is confidential, the related data is rarely published by the pump manufacturing factory and is lacked in literature. Table A shows that most components of pumps are made from ferrous materials of stainless steel and cast iron, and this implies ferrous materials-related energy consumption accounting for the vast majority of the energy consumption in the whole manufacturing process of the pump. Therefore, for the calculation of $E_{embodied}$ in Eq. (6), this study mainly focuses on the ferrous material-related energy consumption, namely the energy consumption in iron ore mining, iron and steel production, and ferrous metal casting.

The amount of iron ore needed for producing one tonne of iron or steel is dependent on the grade (i.e. iron content) of iron ore [27]. Typically, it needs 1.6 tonnes of iron ore for the manufacture of a tonne of pig iron in the global steel industry nowadays [28]. Therefore, C_1 is assumed to be 1.6 in this study. Meanwhile, it assumes that the pump weight is equal to the amount of metal that is processed in the stages of metal production and casting, namely $C_2 = C_3 = 1$.

The pump payback period is proposed based on the comparison of pump embodied energy $E_{embodied}$ and the saving of the operational energy consumption after replacement of the pump, as shown in Eq. (7), where τ_r is the pump replacement period, τ_p is the pump payback period, i is the time (year) of the pump operation, $E_{pump,i}$ and $E_{pump,tr+i}$ are the operational energy consumption at the year of i and τ_r+i. As shown in Eq. (7), the additional energy consumption due to pump replacement, namely the embodied energy of pump $E_{embodied}$, is supposed to be offset by the savings in operational energy consumption after the replacement of a new pump. The pump payback period can be used for the justification of pump replacement; it means only when the payback period is less than the replacement period, the pump replacement at the suggested replacement time is acceptable.

$$E_{embodied} - \sum_{i=1}^{\tau_p}\left(E_{pump,\tau_r+i} - E_{pump,i}\right) = 0 \quad ; \; i = 1, 2, 3, \ldots, \tau_p \qquad (7)$$

Fig. 1 demonstrates the correlation between time t (years) and the cumulative energy consumption E for the situations with and without pump replacement. As shown in Fig. 1, at Point 1 (e.g. time t_r), there is a step increase of the cumulative energy consumption (e.g. pump embodied energy) as the pump replacement; at Point 2 (e.g. time t_p), the cumulative energy consumptions for situations with and without pump replacement are equal. The pump replacement period τ_r shown in Fig. 1 is determined based on Eq. (1), and the pump payback period τ_p is determined by Eq. (7).



E_1 : Cumulative energy consumption for the situation without pump replacement

E_2 : Cumulative energy consumption for the situation with pump replacement at time t_r

Fig. 1. Replacement and payback periods of the pump from the environmental aspect.

The research framework is shown in Fig. 2.

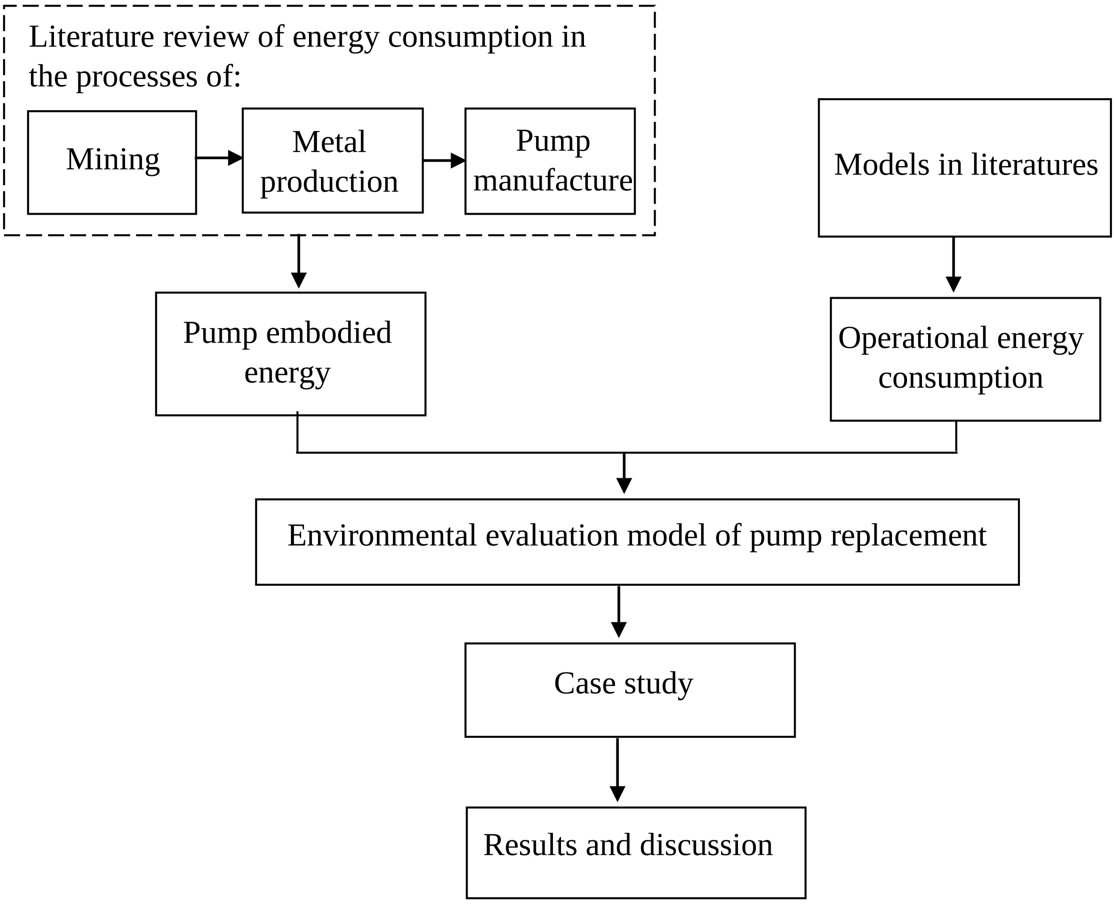


Fig. 2. Research framework diagram.

3. Literature review of energy consumption in mining, metal production, and casting

3.1. Energy consumption in iron ore mining

A typical mining activity includes extraction, material handling and transport, and mineral processing [29], as shown in Fig. 3. By these mining processes, the size of mineral rocks is reduced and the concentration of the minerals is upgraded. These mining processes are accompanied by a great expenditure of energy and it is assessed that the energy consumption in the mining and mineral industry accounts for 4-7% of the overall amount of energy generated globally [30]. The main type of energy source in mining processes is electricity and diesel oil [27, 31-34].

Fig. 3. Main processing stages in mining [29].

As the published data about the energy intensity in iron ore mining is limited, only two reliable references are selected and reviewed in this part, e.g. Norgate and Haque's study [27] and Holmberg et al.'s study [29]. It can be forecasted that with the further refinement of the iron ore mining data, and the result of energy intensity in iron ore mining will be progressively updated. The energy consumption for producing 1 tonne of iron ore for shipment was 152.7 MJ by Norgate and Haque's study [27], while in Holmberg et al.'s study [29], the energy intensity was 18-36 MJ/t ore for surface mining and 72-180 MJ/t ore for underground mining, as summarized in Table 1. In Norgate and Haque's study [27], the energy intensity includes the energy consumption in mining processes of drilling, blasting, loading and hauling, crushing and screening, stacking and reclaiming, rail transport, and port operations. Holmberg et al.'s study [29] did not give the boundary definition of the mining steps included in the estimation of energy intensity. The boundary definition is one of the factors that influence the value of mining energy intensity in different studies. Meanwhile, it should be noted that the energy intensity in Holmberg et al.'s study [29] is the average value for mining ores not only of iron rock but also of coal and copper. This might compromise the data quality for energy intensity in iron ore mining, but the data reported by Holmberg et al. [29] is still valuable for this study as limited literature can be found at the current time.

Table 1

Summary of energy intensity in mining.

Ore mined	**Mining method**	**Energy intensity (MJ/t ore)** e_{minig}	**Reference**
Iron ore	Surface mining	152.7	[27]
No classification	Surface mining	18.0–36.0	[29]
No classification	Underground mining	72.0–180.0	[29]

3.2. Energy consumption in metal (iron and steel) production

The iron and steel production system include multi-level processes, such as sintering, coking, casting, rolling, etc. [35], and energy is consumed during these processes. In practice, the involved processes for iron and steel production may vary with the requirement of the final product. A flowchart of the iron and steel production is presented in Fig. 4. Blast furnace/basic oxygen furnace (BF/BOF) and electric arc furnace (EAF) are two basic routes of steel production nowadays, in which BF/BOF route attributes around 74% of the steel production in the world and EAF steelmaking accounts for about 26% [36].

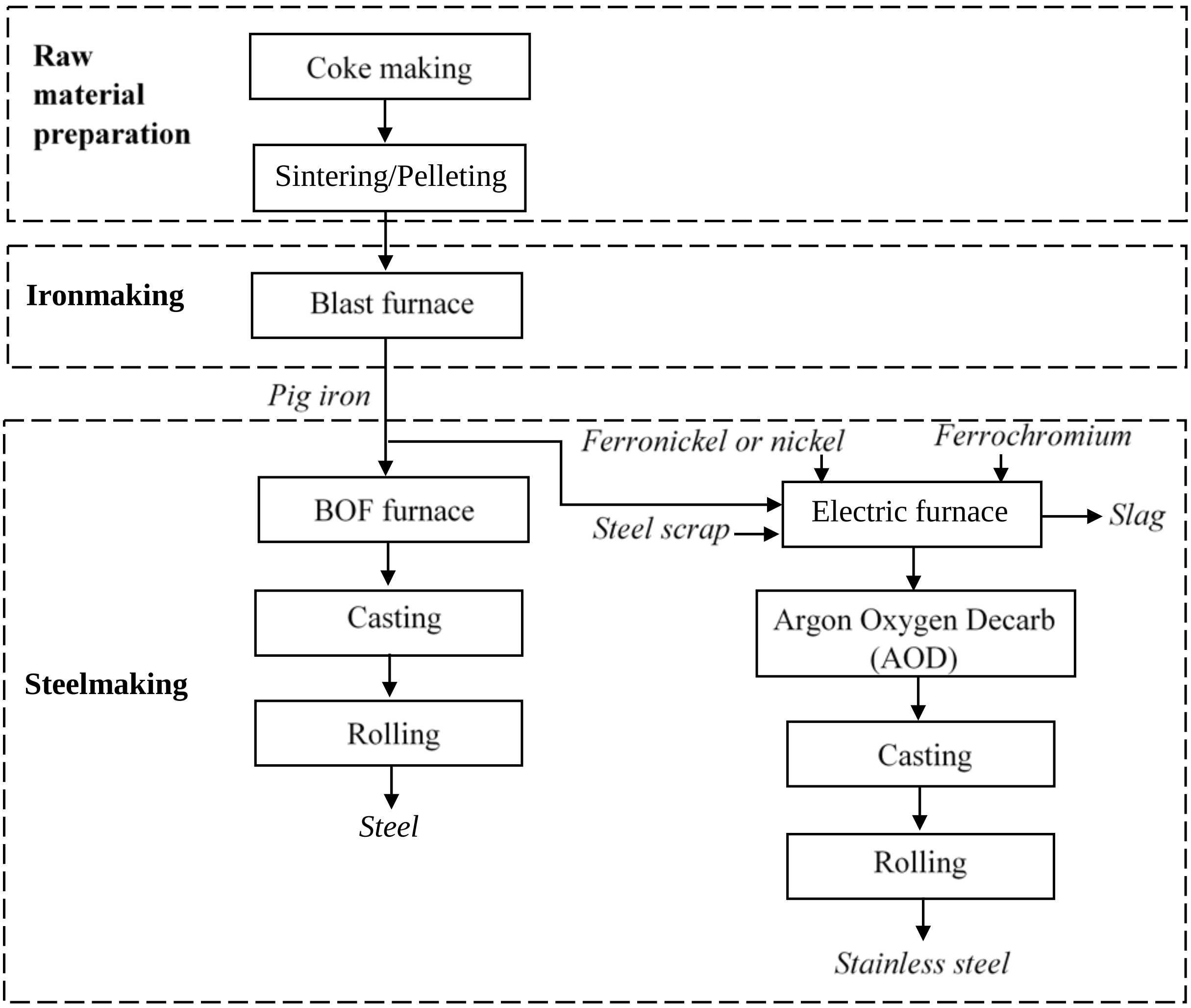


Fig. 4. Flowchart of the iron and steel production [37-39].

Production of iron and steel is an energy-intensive manufacturing process, and it is indicated that the iron and steel industry consumes 18% of the overall energy usage by the industry globally in 2013 [40]. The energy efficiency of iron and steel production varies greatly with countries and plants, for example, it has been reported that the difference in energy efficiency in different countries can reach 50% [41]. The energy efficiency difference of iron and steel production is caused by the variation in the size of iron and steel plants, recovery level of energy from waste, and grade of iron ore [41]. Norgate et al. [38] also pointed out several factors that affect the environmental impact of the metal production process, including the grade of ore, category of source for electricity generation, types of fuel, carriage of substances, and technology of production process.

In literature, energy consumption/intensity and environmental impact (e.g. greenhouse gas emissions) are commonly estimated based on the boundary definition of iron and steel production, and the boundary definition by different studies is usually different [42].

Table 2 summarizes the energy intensity in iron and steel production by different studies. China and the USA are two major steel-producing countries worldwide, in which China produced about 50% of the world's total crude steel in 2014 [36]. Therefore, to some extent, the data in Table 2 can reflect the current situation of energy intensity in iron and steel production globally. The energy intensity data in Table 2 is obtained based on the different boundary definitions of iron and steel production. In Hasanbeigi et al.'s study [43], the boundary of the iron and steel production includes coke making to galvanizing. Chen et al.'s study [37] considered seven processes of iron and steel production. In Burchart-Korol's study [44], the steel plant system includes processes in various plants and furnaces. In Norgate et al.'s study [38], the inventory data for calculating the energy intensity of iron and steel production are averaged over several sources where possible, therefore, this results in the boundary definition include three to five processes. The data of energy consumption for steel production in China also includes the energy consumed by various functional areas related to steel production [45]. The difference in boundary definition makes it difficult to compare the energy consumption/intensity and environmental impacts of iron and steel production by different studies, however, Table 2 still gives a reference value or range of the energy intensity for the current global situation of iron and steel production.

Table 2

Summary of the energy intensity in iron and steel production.

Metal	Country	Process	Energy intensity e_{metal}	Unit	Remark	Reference
Iron	N/A	Scrap/EAF route	4.0–6.0	GJ/t	N/A	[46]
Iron	N/A	BF/BOF route	13.0–14.0	GJ/t	N/A	[46]
Iron	Australia	N/A	22.0	GJ/t	Function unit is 1 kg of refined metal	[38]
Steel	China	N/A	*16.3–17.7	GJ/t	N/A	[47]
Steel	China	N/A	*17.7	GJ/t	In the Year 2012	[37]
Steel	Australia	Integrated route (BF and BOF)	23.0	GJ/t	Function unit is 1 kg of refined metal	[38]
Crude steel	USA	N/A	14.9	GJ/t	Final energy intensity	[43]
Crude steel	China	N/A	23.1	GJ/t	Final energy intensity	[43]
Crude steel	USA	N/A	20.0	GJ/t	Primary energy intensity	[43]
Crude steel	China	N/A	26.3	GJ/t	Primary energy intensity	[43]
Cast steel	Poland	EAF	8.1	GJ/t	N/A	[44]
Cast steel	Poland	BOF	35.4	GJ/t	N/A	[44]
Stainless steel	Australia	Electric furnace and Argon-Oxygen decarburization	75.0	GJ/t	Function unit is 1 kg of refined metal	[38]

Note:

Final (or site) electricity excludes the energy consumed for electricity generation, transmission, and distribution [43].

*Calculated from coal equivalent (ce), based on 1 kgce = 29.3 MJ

N/A: Not applicable

3.3. Energy consumption in ferrous metal casting

Metal casting is reported among the nine most energy-intensive industries [48], and electricity is the main energy consumption source for metal casting [49]. A common modern casting process consists of several stages [50], and the process flow for a typical ferrous metal casting operation is shown in Fig. 5. Three basic melting techniques are employed in ferrous metals, namely cupola, induction melting, and arc melting [48], as shown in Table 3. The type of molding where molten metal is poured into includes green sand molding and "Air set". For the green sand molding, it combines silica or lake sand with clay, water, and certain additions [48]. The "Air set" sand casting uses dry sand bonded with a fast curing adhesive other than clay [51].

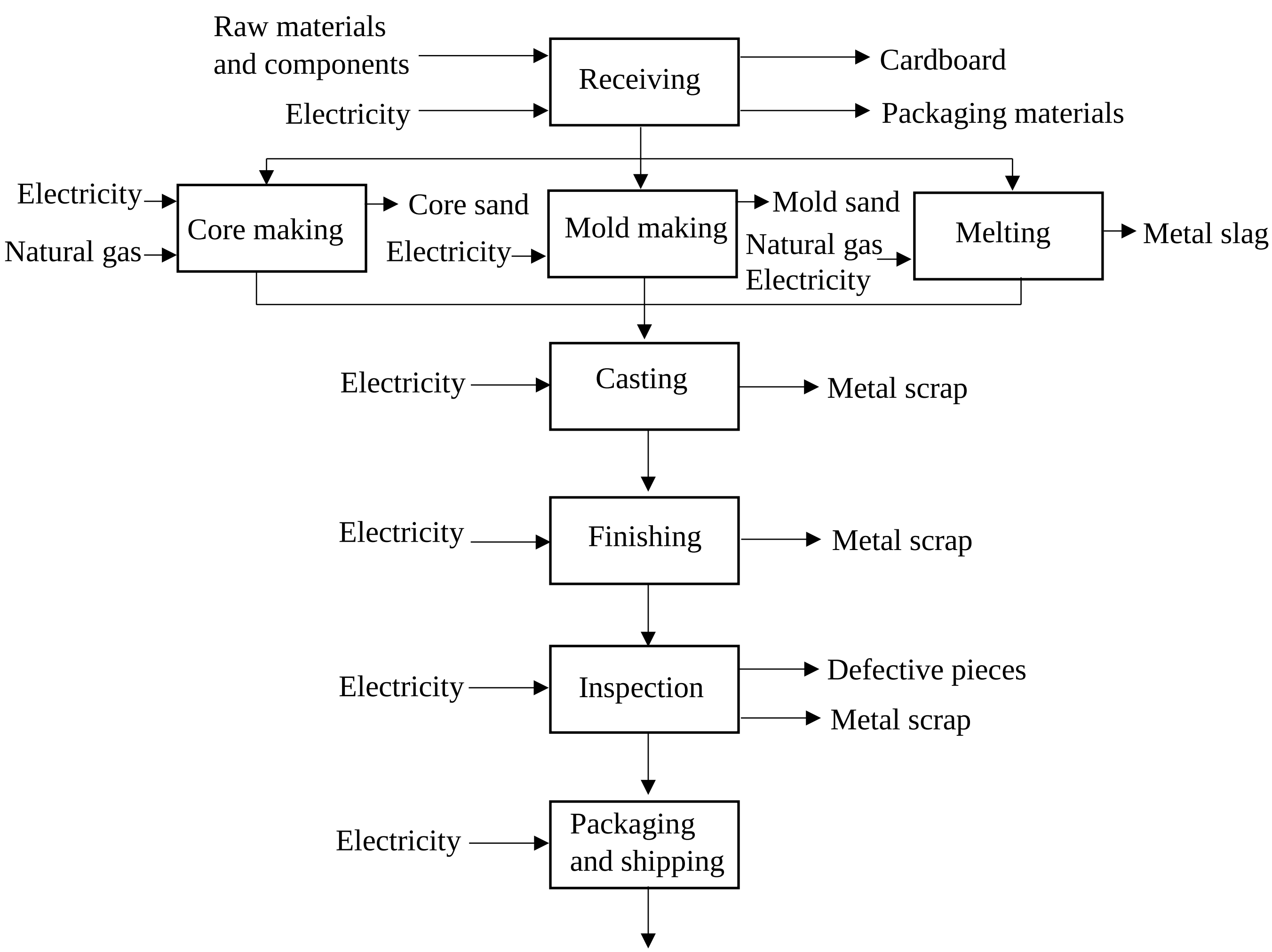


Fig. 5. Process flow for a typical ferrous metal casting operation [48].

Due to confidentiality, published data on the energy consumption of metal casting is rather limited. Only one reliable reference is obtained and reviewed in this part, and the data of the energy intensity in metal casting is summarized in Table 3. As Table 3 shows, the energy intensity in casting varies with the metal types (e.g. gray iron, ductile iron, and steel), melting techniques (e.g. cupola, induction melting, and arc melting), and modeling types (e.g. green sand molding and "Air set").

Table 3

Summary of energy intensity in metal casting [48].

Metal	**Melting technique**	**Molding process**	**Energy intensity (GJ/t)** $e_{casting}$
Gray iron	Cupola	Green sand	14.2
Gray iron	Induction	Green sand	42.6
Ductile iron	Cupola	Green sand	15.5
Ductile iron	Induction	Green sand	32.2
Steel	Induction (Primarily stainless)	Air set	102.3
Steel	Arc	70% Green sand, 30% Air set	39.9
Steel	Induction	Air set	31.8

4. Case study

Pump replacement period of water pump samples with five different pump motor ratings (i.e. 1.1kW, 5.5 kW, 11 kW, 22 kW, 45 kW) are evaluated by the comparison of accumulated extra energy consumption and pump embodied energy. The water pump samples are selected from a series of centrifugal pumps manufactured by a large pump enterprise in China in 2017. All the sample pumps are manufactured by a single enterprise and in line with the requirement of ISO (International Organization for Standardization) 2858 and can be applied in high-rise water systems of buildings. The parameters of sample pumps, e.g. pump weight and design efficiency, are obtained from the brochures published by the company and summarized in Table 4. The pump motor rating of 1 – 40 kW is typical in high rise water supply systems of the building [18], and the specific pump motor ratings of sample pumps, e.g. 1.1 kW, 5.5 kW, 11 kW, 22 kW, 45 kW, are dependent on the product manufactured by the company.

Table 4

Parameters of pump samples.

Pump motor rating (kW)	Number of sample pumps	Pump weight (kg)			*Pump efficiency (%)		
		Range	Ave.	sd	Range	Ave.	sd
1.1	11	35–48	42	4.1	29.0–66.4	50.4	13.6
5.5	11	88–136	111	11.6	19.5–72.1	53.6	19.4
11	22	125–365	189	69.9	35.9–75.8	63.1	15.0
22	16	230–490	332	86.5	40.2–77.9	68.2	12.2
45	16	344–982	632	214.3	50.3–79.3	71.8	8.9

Note: Ave.=average; sd=standard deviation; *Pump efficiency: the pump efficiency on the pump nameplate, which is the efficiency of pump that operates at rated flow.

The parameter values for the water supply pumps in this study are listed in Table 5.

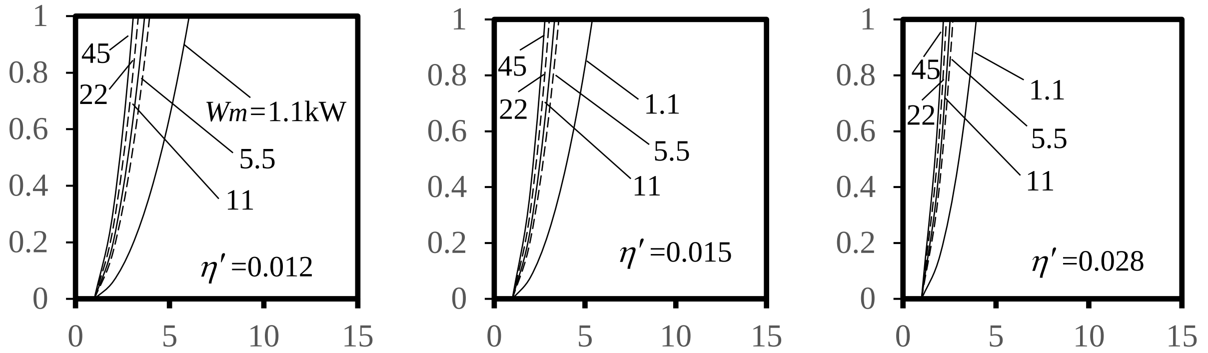
Table 5

Parameter values for water supply pump in buildings.

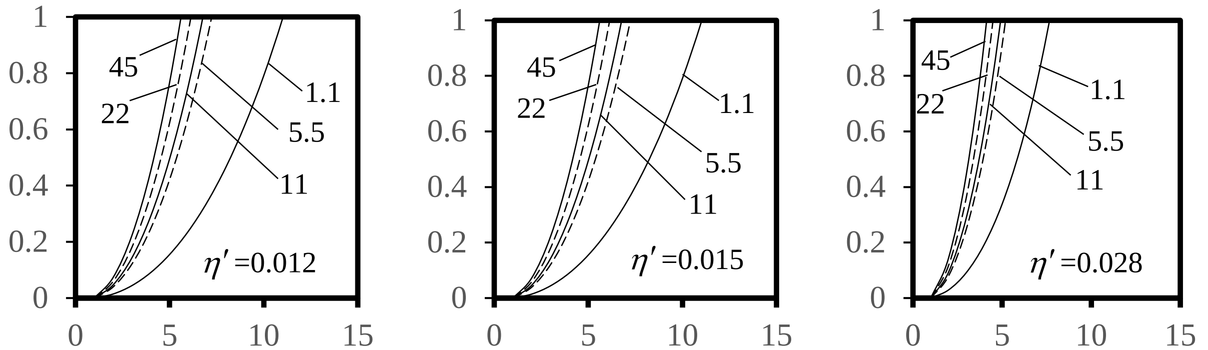
Parameter	Value	Unit
e_{mining}	18.0–180.0	MJ/t ore
e_{metal}	4.0–75.0	GJ/t iron and steel
$e_{manufacture}$	14.2–102.3	GJ/t iron and steel
$e_{embodied}$	18.2 – 177.6	GJ/t iron and steel
$\eta_{c,1}$	0.504–0.718	N/A
η'	0.012–0.028	N/A
W_m	1.1–45	kW

5. Results and discussion

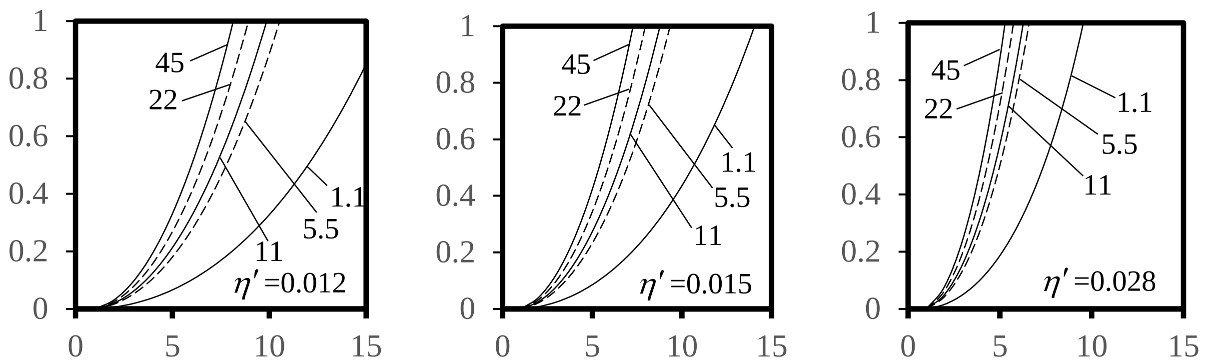
The replacement periods of the pump samples in the W_m range of 1.1 – 45 kW are examined, as shown in Fig. 6. The pump replacement time is obtained from the x-coordinate of Fig. 6 when the ratio of cumulative extra energy consumption to the embodied energy of the pump (i.e. y-coordinate) is equal to 1 (i.e. $\sum_{i=1}^{t_s}\left(E_{pump,i} - E_{pump,1}\right) = E_{embodied}$ in Eq. (1)). Fig. 6 reveals the results for cases under the best-case, average-case, and worst-case scenarios of pump efficiency drop (i.e. η'=0.012, 0.015, and 0.028). Three cases are examined; case (a) is with the minimum energy intensity of pump $e_{embodied,min}$ = 18.2 GJ/t iron and steel, case (b) is with the average energy intensity of pump $e_{embodied,ave}$ = 97.9 GJ/t iron and steel, and case (c) is with the maximum energy intensity of pump $e_{embodied,max}$ = 177.6 GJ/t iron and steel. The example results of replacement and payback periods for pump samples are summarized in Table 6.



(a) The replacement period for cases with the minimum energy intensity of pump $e_{embodied,min}$



(b) The replacement period for cases with the average energy intensity of pump $e_{embodied,ave}$



(c) The replacement period for cases with the maximum energy intensity of pump $e_{embodied,max}$

x-axis: installation time *t* (years) ; y-axis: $\sum_{i=1}^{t_s}(E_{pump,i} - E_{pump,1})/E_{embodied}$

Fig. 6. The ratio of cumulative extra energy consumption to the embodied energy of the pump.

Table 6

Example replacement and payback periods of pump samples.

Pump motor rating W_m (kW)	Annual efficiency drop								
	η'=0.012	η'=0.015	η'=0.028	η'=0.012	η'=0.015	η'=0.028	η'=0.012	η'=0.015	η'=0.028
	Replacement period τ_r for cases with $e_{embodied,min}$			Replacement period τ_r for cases with $e_{embodied,ave}$			Replacement period τ_r for cases with $e_{embodied,max}$		
1.1	6.1	5.4	4.0	12.5	11.1	7.7	16.1	14.1	9.6
5.5	4.0	3.6	2.7	8.2	7.3	5.2	10.6	9.4	6.6
11	3.7	3.3	2.5	7.6	6.8	5.0	9.9	8.8	6.3
22	3.3	3.1	2.3	6.9	6.2	4.5	9.0	8.0	5.8
45	3.1	2.8	2.2	6.3	5.6	4.2	8.2	7.3	5.3
	Payback period τ_p for cases with $e_{embodied,min}$			Payback period τ_p for cases with $e_{embodied,ave}$			Payback period τ_p for cases with $e_{embodied,max}$		
1.1	2.0	1.8	1.3	4.3	3.4	2.2	4.9	4.1	2.3
5.5	1.3	1.1	0.7	2.8	2.4	1.5	3.8	3.2	2.0
11	1.2	1.0	0.6	2.8	2.5	1.7	3.8	3.3	1.9
22	1.0	0.8	0.5	2.7	2.1	1.4	2.5	3.1	1.9
45	0.8	0.9	0.4	2.2	2.0	1.2	2.9	2.6	1.6

As shown in Table 6, the payback periods for all pump samples are shorter than the replacement periods of the corresponding pumps. This means that the pump replacement periods obtained by the proposed model in this study (i.e. Eq. (1) to (6)) are acceptable, and the pump replacement period is justified. As Table 6 shows, a longer pump replacement period is noticed at the greater energy intensity of pump $e_{embodied}$ (the maximum difference of the replacement period can be about 10 years for the pumps with maximum and minimum embodied energy) and a higher annual efficiency drop η' justifies a shorter pump replacement period. Besides, it is observed that larger pumps (e.g. W_m = 45 kW) are justified with a shorter replacement period. Absolute gradient $\left|\frac{d\tau_r}{de_{embodied}}\right|$ and $\left|\frac{d\tau_r}{d\eta'}\right|$ are defined to indicate the sensitivity of the pump replacement period to the pump energy intensity and annual efficiency drop respectively. It is found that the replacement periods of smaller pumps are more sensitive to the pump energy intensity and annual efficiency drop (e.g. $\left|\frac{d\tau_r}{de_{embodied}}\right|$ = 0.058 and 0.033 at W_m = 1.1 kW and 45 kW, respectively; $\left|\frac{d\tau_r}{d\eta'}\right|$ = 376.4 and 167.0 at W_m = 1.1 kW and 45 kW, respectively).

In practical application, the pump replacement period is justified based on the annual efficiency drop and pump energy intensity, in which the pump energy intensity is highly dependent on the material of the pump. As Table 2 and Table 3 show, the pump material of stainless steel is usually with high energy intensity when compared with other ferrous materials, such as iron. Pumps manufactured from stainless steels are suggested with a longer replacement period, however, the service period will be compromised by a high annual efficiency drop. This means that pumps manufactured from materials (e.g. cast iron) with less energy intensity, the corresponding corrosion resistance of the materials might be less than that of the stainless steel, can also get a longer service period if with less annual efficiency drop. For example, as Table 6 shows, at the maximum energy intensity of pump $e_{embodied,max}$, the replacement period τ_r for pumps of W_m = 1.1 kW is justified to be 9.6 years at annual efficiency drop η'=0.028; comparatively, at the average energy intensity of pump $e_{embodied,ave}$, τ_r can be 12.5 years at η'=0.012. The annual efficiency drop of installed pumps significantly influences the replacement frequency of the pump and the total environmental impact (e.g. energy consumption).

In Hong Kong, the suggested pump life of 15 years is adopted in some local standards/guidelines. As shown in Table 6, a shorter pump replacement period is demonstrated based on the evaluation from the environmental aspect (i.e. energy consumption), except for pumps of W_m = 1.1 at $e_{embodied,max}$ and η'=0.012. Evaluation results of pump replacement period based on the economic justification (i.e. cost) in the previous study [18] shows that pump replacement periods for W_m = 1 kW at η' = 0.012, 0.015, 0.028 are 24 years, 19 years, and 13 years respectively; pump replacement periods for W_m = 40 kW at η' = 0.012, 0.015, 0.028 are 10 years, 8 years and 6 years respectively. Comparing with the results of pump replacement periods for W_m = 1.1 kW and 45 kW at $e_{embodied,max}$ in Table 6, the pump replacement period evaluated on the environmental ground is comparable with that evaluated on the economic ground. However, for pumps manufactured from materials of less energy intensity (e.g. $e_{embodied,min}$, $e_{embodied,ave}$), a shorter replacement period is suggested based on the environmental ground when compared with that evaluated on the economic ground; for pumps with $e_{embodied,min}$ and $e_{embodied,ave}$, the replacement periods evaluated on the environmental ground is 63-75% and 30-48% respectively less than that evaluated on the economic ground.

As carbon footprints are progressively included in the cost structure of metal production and manufacturing process (e.g. pump manufacture, electricity generation), for example, through carbon taxes, the installation cost of a new pump and operation cost will increase and there will be a relative shift. The energy evaluation results in this study, such as the pump energy intensity, also provide a reference database for further evaluation of pump replacement periods based on the economic ground with carbon emission cost included.

6. Conclusions

Improving the energy efficiency of water supply systems for buildings is a sustainable development strategy for buildings at the moment. Replacement of aged, poorly maintained, and mismatched pumps with new and high-efficiency pumps will reduce the operation energy consumption of the water supply system, however, additional energy consumption will be caused which is embodied in the new pump manufacturing. This study is the first trial to introduce the environmental evaluation into the replacement period justification of water supply pump in buildings in light to minimize the total environmental impact (i.e. energy consumption) of the water supply system. An environmental evaluation model of the pump replacement period was proposed based on the comparison of the accumulated extra energy expenditure in the long-term operation to the pump embodied energy. Pump embodied energy was obtained based on the literature review of the energy consumption in mining, metal production, and pump manufacture. The results of this study showed that for common pump motor rating ranging from 1.1 kW to 45 kW, with annual efficiency drop and pump energy intensity that ranges from 0.012 to 0.028 and 18.2 to 177.6 GJ/t iron and steel respectively, the payback periods for all pump samples are shorter than the replacement periods of the corresponding pumps. This means that the pump replacement periods obtained by the proposed model in this study are acceptable, and the pump replacement period is justified. A longer pump replacement period is noticed at the greater energy intensity of the pump, and a higher annual efficiency drop justifies a shorter pump replacement period. It was observed that larger pumps (e.g. W_m = 45 kW) are justified with a shorter replacement period. Besides, it was found that the replacement periods of smaller pumps are more sensitive to the pump energy intensity and annual efficiency drop. Moreover, it revealed that for pumps with the maximum embodied energy intensity (i.e. 177.6 GJ/t iron and steel), the pump replacement period evaluated on the environmental ground is comparable with that evaluated on the economic ground. In practical application, pumps manufactured from materials (e.g. cast iron) with less energy intensity, the corresponding corrosion resistance of the materials might be less than that of the stainless steel, can also get a longer service period if with less annual efficiency drop. The study results provide an alternative solution of pump replacement period for typical pump size and pump efficiency drop in water supply systems of buildings. Along with that carbon footprints are progressively included in the cost structure of product manufacturing, the study results can also be a reference database for further evaluation of pump replacement periods based on the economic ground with carbon emission cost included.

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Appendix A

Table A.1

Summary of construction materials of pumps [26].

Pump type	Materials of construction								
	Casing	**Impeller**	**Shaft**	**Sleeves**	**Casing rings**	**Shaft nuts**	**Stuffing box housing**	**Glands**	**Lantern ring**
Fresh water pump for potable application	Stainless steel	Stainless steel	Stainless steel	Stainless steel	Stainless steel	Stainless steel	Gunmetal	Bronze	Bronze
Fresh water pump for non-potable application	Cast iron	Zinc free bronze (*cast iron or stainless steel)	Carbon steel (*stainless steel)	Bronze (*stainless steel)	Bronze (*stainless steel or cast iron)	Bronze	Cast iron	Carbon steel	Bronze
Flushing water pump	Cast iron	Zinc free bronze (*stainless steel)	Stainless steel	Bronze (*stainless steel)	Stainless steel	Bronze	Cast iron	Carbon steel	Bronze

*Alternative materials