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Review

Feasibility Study and Life Cycle Assessment of Two Air Dehumidification Systems

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Design of new cost-effective and sustainable dehumidification systems is important for both energy savings and environmental impacts. This paper analyzes the economic feasibility study and environmental impacts of two different dehumidification systems A and B. These systems are referred as; desiccant system and traditional vapor compression system; respectively. The present worth value and the payback period are used to compare the two systems economically. On the other hand, the weighing methodology of the environmental priority strategies (EPS-2000) has been used for evaluating their environmental impacts. The analysis shows that system A has a payback period of 7 months with annual running cost savings of about 32.5 % compared with system B also, the overall environmental impacts of system A are nearly 0.68 of that of B. The maximum value of LCC for system A and B is 3860 \$ and 5440 \$; respectively at the end of cycle life. Also, the LCS reaches to 1314 \$ at the energy cost 0.05 \$/KWh and 2109 \$ at the energy cost 0.083 \$/KWh.

Keywords: Economic study; Environmental impact assessment; Life cycle assessment desiccant dehumidification; liquid desiccant.

INTRODUCTION

The energy crisis and environmental regulations and laws enhance the use of energy-efficient and environmentally friendly systems. Unrestrained use of fossil fuel as an energy source has resulted in price hike, increasing pollution accompanied with global warming. Sustainable living requires that we adopt non-polluting renewable energy sources. One of the most cost-effective systems that can use renewable energy sources are desiccant

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Nomenclature

C	cost, \$
d	market discount rate
	annual equivalent-CO_2 emissions, (kg/year).
i	interest rate
N	life cycle time, years

Subscripts

IC - initial cost
RC - running cost
S - salvage value

Abbreviations

HVAC - heating ventilating and air conditioning
LCA - life cycle assessment
LCC - life cycle cost, $
LCS - life cycle saving, $
PWF - present worth factor
PP - payback period, years
VCS - vapor compression system
initial extra expenditure, $
annual running cost savings, $

dehumidification systems.

Because of the hot and humid climate in Egypt, the energy demand for air conditioning is quite extensive. Air conditioning, according to conservative estimates, represents 32% of the electrical energy consumed by the domestic sector (Culotta et al., 1996). In humid climates, the humidity issues are a major contributor to energy inefficiency in heating ventilation and air conditioning (HVAC) devices. The use of liquid desiccant dehumidification systems of supply air is a viable alternative to reduce the latent heat load on the HVAC system and improve efficiency. Furthermore, incorporation of desiccant preconditioning into such systems allows higher percentage of fresh air in the supply stream (Nesreen and Kamel, 2003). With recent advances in desiccant dehumidification, liquid sorbent equipment are becoming even more attractive for air-conditioning applications (Meckler, 1995 : Collier et al., 1990 : Albers et l., 1991 : Griffiths, 1989 : Peng and Howell, 1984).

(Bergero and Chiari, 2010) analysed the performance of a hybrid air-conditioning system using LiCl solution as liquid desiccant. Simulation results revealed that energy savings of almost 50% compared to conventional air conditioning system can be achieved under the given conditions. The effect of variable fresh air ratios on the performance of a liquid desiccant air conditioning was studied by (Niu et al., 2010). It was found that at a fresh air ratio of 40%, maximum COP of 0.97 can be achieved. (Xiao et al., 2011) proposed a novel dedicated outdoor air system (DOAS) consisting of a membrane based total heat exchanger which improves the COP in the range of 19.9-34.8% and stabilizes the temperature and humidity of the inlet air in spite of large variation of ambient air. (Wang et al., 2010) designed a new air-conditioning system of liquid desiccant and evaporative cooling capable of treating ambient air at 35℃ to supply air at 18℃ with specific humidity of about 12–13 g/kg, using 40% LiCl solution as desiccant. At the heat source temperature of 70℃ the COP of the system was up to 0.8. Cooling capacity of the system was 40 kW. (Xiong et al., 2010) developed a novel two-stage liquid desiccant dehumidification system assisted by $CaCl_2$ solution. The thermal coefficient of performance increased from 0.24 to 0.73 compared to the basic system. (Yutong et al., 2010) introduced a transient simulation model and the EnergyPlus were used to study the energy performance and economical feasibility for integrating a solar liquid desiccant dehumidification system with a conventional vapor compression air-conditioning system for the weather condition of Hong Kong. The vapor compression system capacity in the solar assisted air-conditioning system can be reduced to 19 kW from original 28 kW of a conventional air-conditioning system as a case study due to the solar desiccant cooling.

When an advanced liquid desiccant dehumidification system used as a part of DOAS for warm and humid outdoor conditions (dry bulb/wet bulb temperatures of 30℃ /25.6℃), could achieve appreciable energy cost savings of approximately up to 30% relative to conventional systems using conventional reheat as reported by (Dieckmann et al., 2008). In some instances, occupants respond to the poor performance of conventional systems by decreasing the indoor temperature set point to ensure that the unit runs long enough to dehumidify the space. This increases the sensible loads and under this condition the unit provides negligible sensible cooling and very inefficient latent cooling (Kosar, 2006). As a result, liquid desiccant systems can realize significant savings under humid conditions. The energy impact study conducted by (Mei et al., 1992) indicated that 13% energy saving in residential cooling and 8% in commercial cooling is possible with desiccant cooling systems relative to classical cooling systems. (Albers et al., 1991) estimated 5% lower energy consumption and 50% lower operating cost for the liquid desiccant system compared to a conventional cooling system. Recently, the annual performance study using liquid desiccant cooling system is carried out by (Liu et al., 2006) in China for the Beijing climatic conditions. The study reveals that, in summer, when the average latent load of the building covers 30%, primary energy consumption and operating cost are 78% and 75%, respectively, of that of the classical HVAC system. In winter, when the average latent load covers 10%, the primary energy consumption and operating cost are 62% and 57%, respectively, compared with that of a conventional system.

As reported in (Kosar, 2005), significant electrical demand and energy savings can be achieved in supermarkets by reducing indoor humidity to very low levels. With a store HVAC system commonly kept at 24℃/55% relative humidity, electrical use for the low-medium temperature refrigeration will decrease by up to 20% if indoor humidity is lowered to 35%. (Kamel, 2008) introduced a transient performance of a hybrid desiccant vapor compression air conditioning system is numerically simulated for the ambient conditions of Beirut. He reported that, the annual running costs savings for the

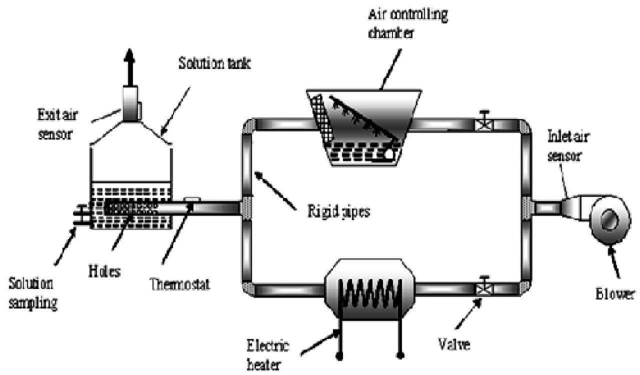

Figure 1. Schematic for system A, desiccant dehumidification system.

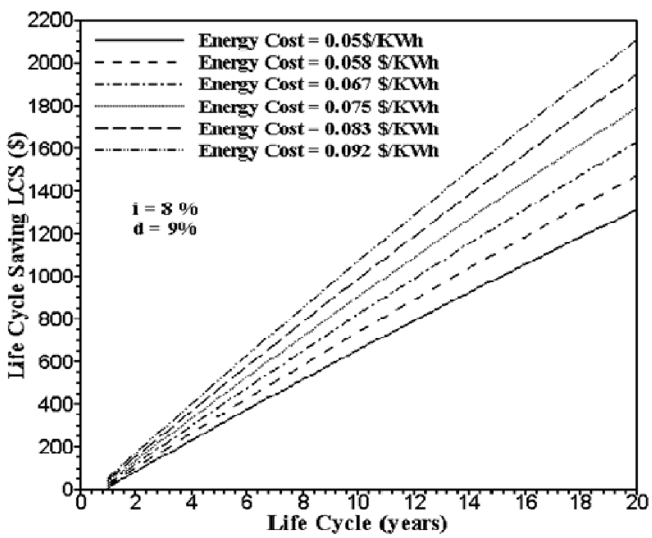

Figure 2. The effect of life cycle on life cycle savings (LCS).

hybrid system is 418.39 USD for a gas cost price of 0.141 USD/kg.

Requirements for the design of HVAC systems with low environmental impacts have become accepted in the past decade. However, the environmental performance is complicated to evaluate, because the process is affected by several parameters. (Katarina, 2004) presented a case study, in which a previously established method for environmental evaluation is adapted. Two alternative air handling units were analyzed using life cycle assessment including the weighting step. The results, according to the weighting method applied as well as the material assumptions, show that the user stage of the life cycle of both units is the critical part of the overall impact. Only a few studies found focused on HVAC systems. (Legarth et al., 2000) analyzed the environmental impacts of an air-conditioning unit using nine impact categories (such as global warming and ozone depletion), four waste categories, and five natural resource categories. (Prek, 2004) evaluated the environmental impact of manufacturing process of three residential heating systems of 11.8kW output: a radiator heating system with metal pipes, a floor heating system with polyethylene pipes, and a fan coil convector heating system. The heat conversion equipment and fittings were not taken into account. The study used the Eco-indicator 95 method to aggregate various environmental impacts into one single indicator. The radiator heating system was found to have the highest environmental impact while the floor heating system has the lowest environmental impact.

In the present work, an evaluation of the economic feasibility analysis and a life cycle assessment (LCA) of a two different dehumidification systems A and B, desiccant system and VCS; respectively, is performed. The aim of this study is to illustrate how the on hand methods and recommendations for the economic feasibility analysis and environmental impact assessment can be used in the design process of dehumidification systems. The

Table 1. Capital cost of both systems

	System		System B
Item	Cost, $	Item	Cost, $
Calcium chloride (25 kg)	12	DX unit (1 TR)	416
Manufacturing and accessories	540	Manufacturing and accessories	75
Overheads	66	Overheads	66
Total capital cost	**618**	**Total capital cost**	**557**

Table 2 Running cost of both systems

		System A			**System B**
Item	**kWh/ day**	**Annual, $**	**Item**	**kWh/ day**	**Annual, $**
Regeneration heat (0.72 kW)	6.48	86	Compressor (1.52 kW)	13.68	182
Pumps and fans (0.38 kW)	3.42	45	Fans (0.21 kW)	1.89	25
Maintenance		25	Maintenance		25
Total annual running cost	**9.9**	**156**	**Total annual running cost**	**15.57**	**232**

outcomes of the economic and environmental study are planned to lay basis for designers' choices during the design phase.

Economic feasibility analysis and LCA

The economic feasibility analysis and LCA are performed in order to evaluate the presented system A economically and environmentally compared to the traditional system B. The schematic diagram of the presented system A is shown in Fig.1. This system is designed, built and experimentally tested by (Kabeel, 2010). The experimental setup of system A was developed to carry out studies on the air injected through the liquid desiccant (calcium chloride) during dehumidification and humidification processes. Solution tank with a dimensions of 40x40 x50 cm contained the desiccant solution is mounted. The tank is made of a galvanized iron sheet with 2 mm thick. A mechanical blower is used to inject the external air through the solution tank with different air mass flow rates. A fan is used to pass an outside air to a three different paths, where only a one path can be used during the experimental work. The first outside air path is directed to the solution. The second air path is directed to the humidifier to control the humidity of the air before the injection into the solution. The third air path passes over an electric heater to rise the air temperature before the injection into the solution. During the experiment, one of the paths is used while the others are closed by using a valve arrangement. The dimension of all ducts used for the three paths have 0.05 m internal diameter. The air is injected through a series of pipes where ten pipes are used to obtain homogonous distribution. The pipes are erected by away to allow the air exit level at 0.01 m from the tank base level to the upper direction in the solution. The air mass flow rate is controlled by using the valve arrangement. An electrical heater with a maximum power of 1.5 kW is used. A thermostat with a maximum controllable temperature of 90 °C is used in regeneration process of the liquid desiccant. The liquid desiccant used in this work has an initial concentration of 40% at different levels in the solution tank. A small air-washer is applied for this work to control the air inlet humidity. Piping connections are used to connect the blower, heater, air-washer and the solution tank. Flexible joints between ducts are erected to damp the noise and vibrations.

Economic Study

There are numerous methods describing any economic feasibility analysis for evaluating any investment. In this study, in order to investigate the economic feasibility, the total cost analysis is taken into account. The evaluation tool is based on the life cycle concept, which is a cradle-to-grave approach to analyze any energy system in its entire life cycle. Costs of the systems are grouped into three categories: costs involved in the construction phase are considered as initial cost for equipment and installation, costs incurred during the operational phase are running costs, and costs are incurred in the end life and disposal of the system while the equipment can have some salvage value. A life cycle cost (LCC), present worth value and the payback period are used to compare the two different systems A and B.

A low-priced system or piece of equipment, for example, might appear initially attractive, but might be excessively costly to operate over its life cycle time or its useful life might be unusually short, making the item of less economic value than other alternatives in the long term. The technique of LCC allows one to move beyond

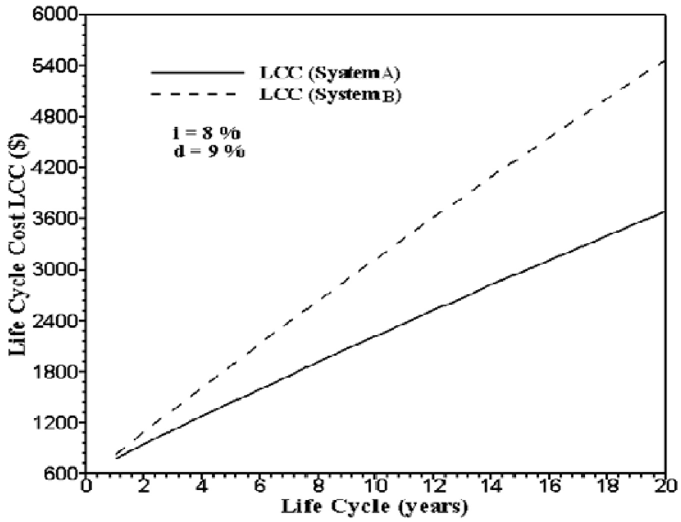

Figure 3. The effect of life cycle on life cycle cost (LCC).

the simple acquisition cost of a piece of equipment to evaluate its long term economic impact on the facility for which it is proposed. The total LCC can be calculated from (Zhai et al., 2009) as follows:

$$LCC = C_{IC} + \sum_{1}^{N} PWF \times C_{RC} - PWF \times C_S \quad (1)$$

where LCC is the life cycle cost, C_{IC}, C_{RC} and C_S are the initial cost, running cost and salvage value of the equipment; respectively and PWF is the present worth factor which can be calculated as follows:

$$PWF = \frac{1}{d-i}\left(1 - \left(\frac{1+i}{1+d}\right)^N\right) \quad \text{if } i \neq d \quad (2)$$

where: N is the life cycle time, i is the interest rate and d is the market discount rate. The life cycle savings (LCS) may be calculated as follows:

$$LCS = PWF \times \Delta C_{RC} - \Delta C_{IC} \quad (3)$$

where: ΔC_{IC} is the initial extra expenditure and ΔC_{RC} is the annual running cost savings.
where:

$$\Delta C_{IC} = C_{IC,System\ A} - C_{IC,System\ B} \quad (4)$$

$$\Delta C_{RC} = C_{RC,System\ B} - C_{RC,System\ A} \quad (5)$$

A simple crude method for getting a quick evaluation of the alternatives is to calculate how long it takes to recover the initial investment, i.e. the payback period (PP):

$$PP = \ln\left(\frac{\Delta C_{IC} \times i}{\Delta C_{RC}} + 1\right) / \ln(i+1) \quad (6)$$

A latent load of 2.12 kW is used to compare the two presented systems. The life cycle time (N) of both systems is assumed to be 20 years. The total capital cost of system A and B have been illustrated with the available material in the Egyptian market in Table 1. The running cost of these systems are calculated using a thermal energy weighting factor of three, (i.e. 1 kWh of electrical energy = 3 kWh of thermal energy in view point of energy weight). The price of one kWh is assumed to be 0.067 $ in average, see Table 2.

Life cycle assessment

A life cycle assessment is an evaluation of the environmental impacts that product or service has during its lifetime. LCA is performed by treating an inventory of relevant inputs and outputs of a product by evaluating the potential environmental impacts associated with the product's life cycle time and by interpreting the results of the inventory analysis and impact assessment phases. The LCA covers the whole life of the product; the study begins from the raw material required for production, use and disposal. LCA study consists of four stages: goal and scope, inventory analysis, impact assessment and interpretation. The main phases of LCA are goal and scope definition (defining aims, product system and reach of the study), inventory (material extractions and emissions caused by the product system are quantified and related to the product function), impact assessment (outcome of the inventory is analyzed with respect to their environmental relevance) and interpretation (results are evaluated with regard to the goal of the study). LCA begins with an organized inventory of all the material resource consumption and emissions during an entire life

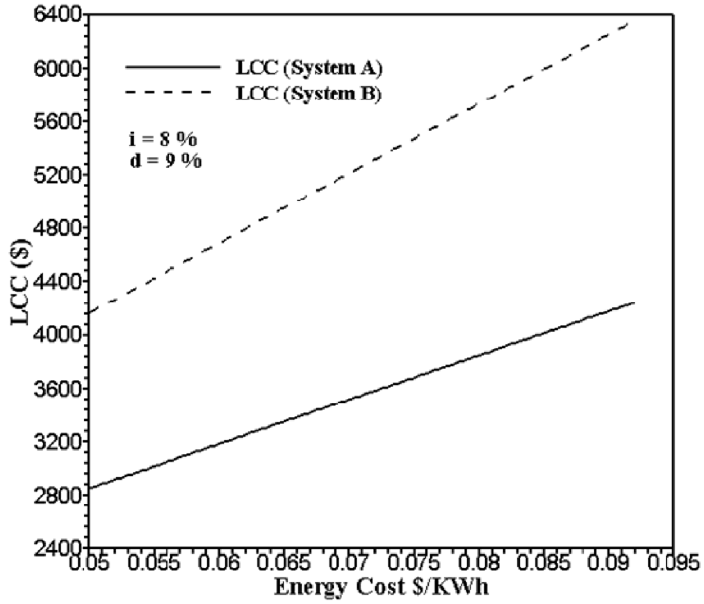

Figure 4. The effect of energy cost on life cycle cost (LCC).

Table 3 Inventory data results of system A and system B and impact indices, EPS-2000 default method

	System A (kg)	System B (kg)	Impact index (ELU/kg)
Material resources:			
Fe ore	16.2	4.3	0.961
Al ore	1.3	5.1	0.439
Cu ore	0.50	0.35	208
Oil (in the ground)	4658	6943	0.506
Emissions to air:			
Co_2	25486	38429	0.108
Hcl (reaction of $CaCl_2$ and H_2O	49.75	0	2.13
HFC-134a	0	1.2	487

cycle of the product. One source of the environmental impacts of energy usage may be classified into two major items: the global warming potential (GWP) and the impact of CO_2 emissions. Both of these items may be converted to equivalent-CO_2 emissions. GWP has become an issue of great interest to the public. Here, the annual equivalent-CO_2 emissions can be calculated from (Zhentao and Radu, 2009):

$$EE_{CO_2} = \frac{\beta_1 E_{gas} + \beta_2 E_{oil}}{1000} \qquad (7)$$

where:

EE_{CO_2} : is annual equivalent-CO_2 emissions (kg/year).

E_{gas} and E_{oil} : are the annual energy inputs (kWh/year) from gas and oil resource.

β_1 : is the specific equivalent-CO_2 emissions (kton/TWh) from gas fired power plants. It is estimated to be 443 kton/TWh.

β_2 : is the specific equivalent-CO_2 emissions (kton/TWh) from oil-fired power plants. It is estimated to be 778 kton/TWh.

The result of this inventory is a list of emissions, consumed resources and non-material impacts like land use. This table is termed the inventory result. Since usually inventory tables are very long and hard to interpret, it is common practice to sort the impacts by the impact category and calculate a score for impact categories such as greenhouse effect, ozone layer depletion, and acidification. Once the category indicator results are generated, additional techniques are used to analyze the category indicator results (normalization) and

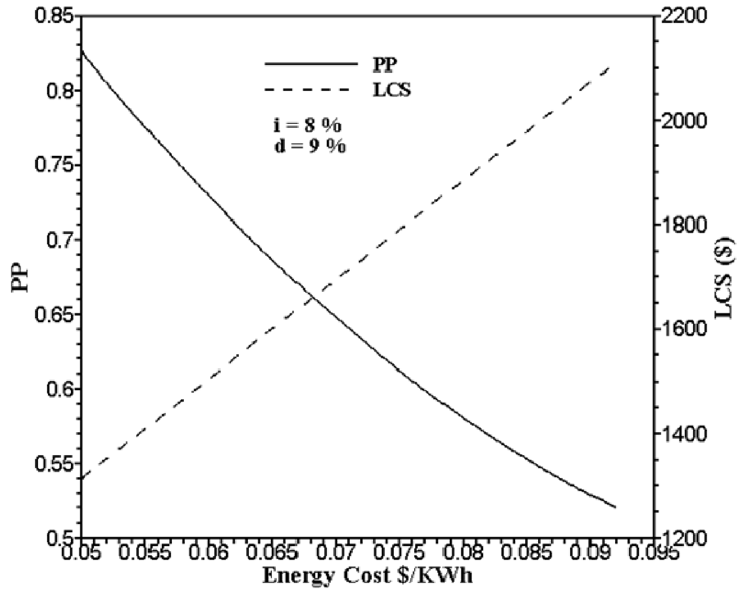

Figure 5. The effect of energy cost on life cycle saving (LCS).

the valuation process to aggregate across impact categories (valuation or weighting).

Goal and scope of study

The aim of this study is to evaluate the environmental impact of desiccant dehumidification system for dehumidifying air (System A) taking into account its entire life cycle. Results of this study are planned to supply both designers and decision makers with relevant information about the environmental performance of this system, and thus to enable them to identify possible modifications of the system design to improve the environmental performance of similar systems. The desiccant dehumidification system is compared with a traditional air-dehumidification system (System B). The two systems are as follows:

- System A, as shown in Fig. 1, consists of an air distribution cycle (air ducts, supply air blower, some fittings), desiccant solution cycle (solution tank and air washer) and the system energy source for heating (electric heater). The electric heater is used to heat supply air for desiccant regeneration in humidification mode.
- System B, traditional VCS, consists of a compressor, condenser and an air distribution system (fans and ducts). The source of cooling energy is an ordinary evaporator.

Evaluation method and inventory data

The application of a weighting method was chosen as an appropriate methodology for the aforementioned study. In accordance with the goal, the overall environmental impact of each life cycle phase of the presented systems is considered, as well as the environmental impact of materials should be presented. The information about the environmental performance of materials is important in the early design process. Accordingly, the designers should be provided with relevant information about the environmental impact of the systems. In addition, the inventory data results should also be presented, to enable further analysis in the decision-making process, as well as to be used for the external communication, e.g. between the design company and their clients.

These requirements can be met by applying a weighting method. Here, the weighting methodology EPS-2000 default method was used for the evaluation of the environmental impact. The weighting principles of the EPS-2000 default method are based on society's willingness to pay to avoid damaging the environment.

The methodology is continuously developed and updated. The principles are published and accessible (EPS http:/www.cpm.chalmers.se/cpm/public/publicat.htm,2002). Thus, the transparency of the weighting values as well as the impact indices is ensured. The environmental impact indices are expressed here in environmental load unit (ELU) per kg (ELU/kg). The environmental assessment is based on inventory data for materials and energy sources used to produce and maintain the presented systems. When the inventory data were not available for some materials, data for substitution materials were used. Finally, the overall environmental impact including material resources depletion and emissions to air due to energy usage of each life cycle of the two systems is considered.

Economic and life cycle assessment results

From the economic analysis, the difference in capital cost (ΔC_{IC}) is 61 $ as shown in Table 1 and the difference in annual running cost (ΔC_{RC}) is 76 $ as shown in Table 2. The capital cost of system A is financed over 20 years at market discount rate d = 9% and the annual cost payments are expected to inflate at a rate of i = 8%. The payback time is found to be 7 months. The payback period of system A is less than one year and it will achieve an annual running cost savings of about 32.5 % compared with traditional system B. This may emphasizes the need of incorporating the desiccant system along with air conditioning applications. System A achieves a total LCS of about 602 $ at the end of its life cycle. Also, the total life cycle cost of system A is found to be about 21.34% less than that of system B, the salvage value is assumed to be zero for both systems. The effect of life cycle on LCC and LCS is shown in Figs. 2 and 3. From Fig. 2, the LCS directly increases by increasing the life cycle at different energy cost. Increasing the energy cost from 0.05 $/kWh to 0.083 $/kWh, the LCS increases by about 150% at the end of cycle life. On the other hand from Fig. 3, the rate of increasing the LCC of system B is greater than system A. The maximum value of LCC for system A and B is 3860 $ and 5442 $; respectively at the end of cycle life. The effect of energy cost on LCC, LCS and PP is shown in Figs. 4 and 5. From Fig. 4, by increasing the energy cost, the increasing rate in LCC for system B is greater system B, and at an energy cost of .083 $/KWh, it reaches to 4207 $ for system A and 6297 $ for system B. On the other hand, by increasing the energy cost, the PP decreases and reaches to 0.83 years at the energy cost 0.05 $/KWh and 0.53 years at energy cost of 0.083 $/kWh. Also, the LCS reaches to 1314 $ at the energy cost 0.05 $/KWh and 2010 $ at the energy cost 0.083 $/KWh.

From the LCA, the inventory results for the presented systems A and B, and the impact indices for the EPS-2000 default method are given in Table 3. Here the source of energy is assumed to be oil and 90% of all metals used were recycled. By applying the weighting indices for the emissions and resource depletions determined by the EPS-2000 default method on the inventory results in this table, the overall environmental impacts for both the systems can be calculated.

From Table 3 the overall environmental impacts of system A are nearly 0.68 of the overall environmental impacts of system B. Also, in the two systems the material impacts are very small compared to the impacts of the energy usage and Co_2 emissions. The impact of energy usage is based not only on the quantity of energy used but also on the energy source used for the evaluation (oil, coal, etc.). The impacts of the energy usage and Co_2 emissions are nearly 95.3% for system A and 91.4% for system B, respectively.

CONCLUSIONS

An analysis of the economic feasibility study and environmental impacts of a two dehumidification systems, desiccant system A and traditional vapor compression system (VCS) B has been performed. Economically, LCC, LCS and the payback period are used to compare the two systems A and B. The weighting principles of the EPS-2000 default method are used to assess and compare the environmental impacts of the two systems. The following conclusions can be summarized:

• The total life cycle cost of system A is found to be about 21.34% less than that of system B.

• For a 20 years life cycle time, the life cycle savings of system A are 600 $ without any remarkable increase in the initial expenditure.

• The payback period of system A is 7 months with an annual running cost savings of about 32.5 % compared to system B.

• The maximum value of LCC for system A and B is 640 $ and 906 $; respectively at the end of cycle life.

• The overall environmental impacts of system A are nearly 0.68 of the overall environmental impacts of system B.

• The LCS reaches to 1314 $ at the energy cost .05 $/KWh and 2109 $ at the energy cost 0.5 $/KWh.

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