# Comfortable and high-efficient desiccant-enhanced direct expansion heat pump

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**Abstract**

Comfortable, efficient and affordable heating, ventilation and air conditioning (HVAC) systems in buildings are highly desirable to achieve zero energy building (ZEB) effort. Traditional vapour compression air-conditioners hold a lower COP (coefficient-of-performance) (typically 3.2~3.8) because it often operates at a lower evaporation temperature (5~7$^{o}$C) and a higher condensing temperature (50~55$^{o}$C) caused by cooling-based dehumidification method that handle both sensible and latent load together. Temperature and humidity independent control or desiccant systems have been proposed to overcome these challenges, however, the *COP* of current desiccant systems is quite small and additional heat sources are usually used. In this paper, we report desiccant-enhanced direct expansion heat pump based on water-sorbing heat exchanger by desiccant coating that exhibits an ultrahigh COP value of more than 6 without sacrificing any comfort and compactness. The efficiency is **double** in comparison with current normal room air conditioners, which is a breath-taking and revolutionary progress. This new approach opens up the possibility of designing a ZEB with DDX HP powered by solar PV, and one PV model (265Wp) can effectively handle about 10m$^2$ cooling load in Shanghai in summer.


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*Keywords:* Dehumidification; Water-sorbing heat exchanger; Desiccant-enhanced direct expansion heat pump; Zero energy building

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## 1. Introduction

There is a growing concern that the increasing demand for heating, cooling, and refrigeration services world-wide may consequently lead to global warming and environmental unfriendliness[1-3]. To alleviate this trend, major efforts are being directed at improving thermal performance of building envelopes and enhancing the energy efficiency of building services within them to address the critical needs of the zero energy building (ZEB) effort[4]. However, it is impractical and far too costly to design a ZEB with standard HVAC systems by attempting to generate all the required energy through on-site renewable energy. As noted in [4], the approach for a ZEB is to greatly reduce the energy needs through efficiency gains, and only then make up the remaining energy needs through on-site renewable generation. Although there have been significant breakthroughs in the past decade on alternate efficient cooling technologies such as magnetic[5], thermoelectric[6], elastocaloric[7] and thermoacoustic[5] cooling, most of these ideas have not been translated into viable technologies due to multiple reasons. For example, the maximum cooling demonstrated for magnetic refrigeration10 has been less than 1 kW. Considering that more than 90% of the cooling systems today are based on vapor compression, it is valuable to dramatically improving the energy efficiency of vapor compression based systems while reducing greenhouse gas emissions and the cost to the consumers.

Air-conditioning systems utilizing vapor compression heat pump cycles have seen energy efficiency improvements through reductions in required compressor operation; mainly by decreasing the difference between high and low pressures. Efficiency improvement in this manner requires dispersing temperature rise, which greatly decreases the latent capacity as shown in [8]. In air-conditioning systems there is generally a compromise between efficiency and latent capacity. This is because current air conditioners remove the water vapor from the moisture air by cooling it below the dew point. So it is quite normal that HVAC systems do not provide sufficient humidity control under certain conditions (e.g. when sensible cooling loads are low) and do not offer adequate fresh air ventilation which is necessary to ensure indoor air quality in tight homes but can significantly improve the latent load.

To solve this problem, innovative system designs such as temperature and humidity independent control (THIC) had been proposed[9]. A THIC system usually consists of a thermal driven dehumidification unit (for example liquid or solid desiccant system) and a vapour compression air-conditioner specializing for the sensible heat load. It was reported that THIC systems might save 25~50%[10] electrical consumption by adopting a higher evaporation temperature (e.g.15~20$^{o}$C) and the corresponding COP increases by about 40~60%[10] under different operating conditions compared to conventional HVAC systems. However, the *COP* (=Latent load/primary thermal energy input) of current solid desiccant systems is quite small, typically ranging from 0.5–1.0[11] due to the required high regeneration temperature (usually in the range of 60 to 120$^{o}$C[11, 12]). Even though sometimes solar heat or industry waste heat can be used, a large volume and high utility cost limits their large-scale application in residential buildings.[10]

In recent years, to attenuate these influences, an inter-cooling desiccant heat exchanger has attracted more and more attentions[13-16], but studies mainly focus on air cooling or water cooling desiccant heat exchanger. By this way, the heat released in adsorption process can be carried away quickly by the inner heat transfer media, which is very useful to reduce the regeneration temperature. However, this kind of desiccant heat exchangers still work as a dehumidifier, and need additional cooling and heating sources. All these make the whole HVAC systems complex and expensive.

Considering the thermal regeneration characteristic, it would be reasonable to use the condensing heat for the regeneration of desiccant dehumidification unit and the refrigerant evaporating to keep low adsorption temperature[10]. Then novel desiccant material which has sufficient water adsorption capacity difference at two cycle conditions (such as 15°C /80%RH and 45°C/30%RH) can be adopted. It is estimated that, if the HVAC systems have 40~50% latent heat, latent load is removed by desiccant system and sensible load is treated as before, adsorption heat is removed by refrigerant and desiccant is regenerated by condensing heat, evaporation temperature can increase from about 5~7°C to about 15~17°C, and condensing temperature can decrease from about 50~55°C to about 40~45°C, and then the COP can be nearly doubled.

Here, we report a novel concept of desiccant-enhanced DX heat pump (DDX HP) based on the proposed water-sorbing heat exchanger (WSHE) fabricated by coating desiccant on the surfaces of conventional evaporator and condenser. In order to guarantee continuous operation, two same WSHEs will switch from evaporator (condenser) into condenser (evaporator) alternatively. The sensible load is handled in the same way as before by convection but without overcooling, and coated desiccants treat the latent load in a nearly isothermal way. Therefore, the process air leaving the evaporator satisfies the requirement of supply-air. As a result, the evaporation temperature rises while the condensation temperature drops compared to traditional air conditioners because WSHE need not cool the process air below its dew point to condense the moisture and the adsorbed water evaporating strengthens the heat dissipation capacity of condenser. Therefore, DDX HP shows a great potential to achieve much higher energy efficiency.

## 2. System description

### *2.1. Working principle*

DDX HP can be taken as a combination of traditional VC system and solid desiccant material (Fig.1), which has a return air inlet (RA) and an outdoor air inlet (OA), a supply air outlet (SA) and an exhausted air outlet (EA). In the system, sensible heat exchangers (including evaporator and condenser) within VC cycle is coated with desiccant materials. Because this novel heat exchanger can adsorb water vapor and retain the removed water, which is totally different traditional heat exchanger, we name it water-sorbing heat exchanger (WSHE). It is the same as conventional VC system, refrigerant in DDX HP operates as following: after absorbing heat in the evaporator, refrigerant vapor is compressed in the compressor, condenses in the condenser and expands through the throttling device, then the cold refrigerant goes to evaporator again. Yet, air flow in DDX HP is more complicated compared with VC system. When ambient air is pumped into the evaporator, the air flow will be dehumidified by the desiccant coated on the evaporator surface. At the same time, evaporation inside evaporator will cool down the air flow and also takes away the adsorption heat on the desiccant. Processed air then becomes colder and dryer. On the other hand, another group of air is heated by the hot refrigerant inside the condenser. Meanwhile, the coated desiccant at a relatively high temperature desorbs water vapor into the air.

After a time, adsorption ability of coated desiccant in evaporator reaches to saturation, due to abundant moisture inside. Meanwhile condenser is almost completely regenerated by high temperature refrigerant. Then, it is time to switch over the four-way reserving valve, exchanging position between evaporator and condenser. Thus, DDX HP features a process of periodic switchover of the evaporator and condenser. Air duct should also be re-constructed, to persistently guide cooling air into the condenser.

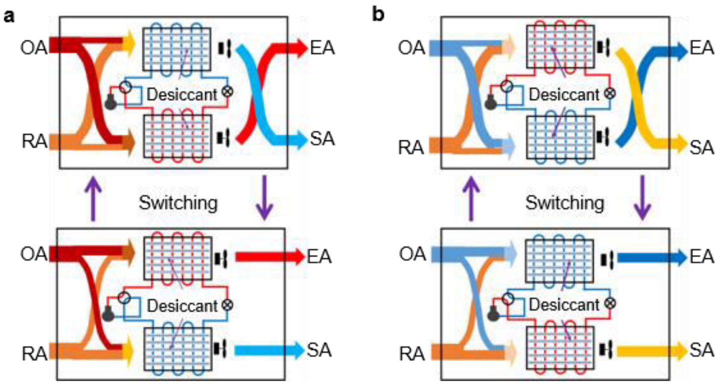


Fig.1. Schematic illustration of the working principle of DDX HP in summer (a) and winter (b).

In this case, WSHE can independently handle the sensible and latent loads at the same time without overcooling or reheating (Fig.2a). Therefore, the process air leaving the evaporator satisfies the requirement of supply-air (Fig.2b). Specifically, the sensible can be adjusted by changing evaporation temperature and the latent load capacity can be managed by altering the duration of moisture uptake respectively. Desiccants absorb moisture almost isothermally and can be regenerated by condensation heat. Evaporation temperature can increase from ~5°C to ~15°C as dew-point condensation is not needed, while condensation temperature could be decreased from ~55°C to ~45°C owing to the enhancement of heat dissipation due to adsorbed water evaporating. So, DDX HP shows a great potential to achieve much higher energy efficiency (Fig.2c).

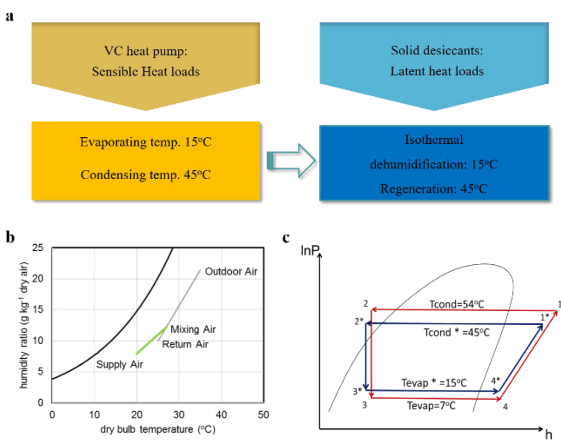


Fig.2. Conceptual design of DDX HP in summer.

## *2.2. Experimental setups*

To demonstrate the feasibility of this novel concept, a single packaged DDX HP was designed and constructed, illustrated in Fig.3. The main parts used is detailed shown in Table 1. In this design, the whole system includes two parts: vapor compression loop and air ducts, both are located in a cabinet with two air inlets (OA and RA) and two air outlets (SA and EA). DDX HP has two operation modes for cooling and dehumidification. (1) 4-way valve 5 were power-off, valve 22 and 25 are open and valve 23 and 24 are closed.

WSHE 6 is condenser and WSHE 7 is evaporator. Outdoor air (OA) and return air (RA) are sucked into the cabinet by two fans 13 respectively. Part of OA passing through valve 18 and part of RA passing through valve 19 are mixed in chamber 26, formatting the process air; while the rest of OA passing through valve 20 and the rest of RA passing through are mixed in chamber 27, formatting the cooling air. Process air flows through valve 22(up) and then into WSHE 7; after being cooled and dehumidified, it passes valve 25(down) and at last is supplied into conditioned room by air duct 16. At the same time, cooling air flows through valve 22(down) and then into WSHE 6; after being heated and humidified, it passes valve 25(up) and finally is exited to the outdoor by air duct 17. (2) 4-way valve 5 are power-on, valve 22 and 25 are closed and valve 23 and 24 are open. WSHE 6 is evaporator and WSHE 7 is condenser. Process air flows through valve 23(up) and then into WSHE 6; after being cooled and dehumidified, it passes valve 24(down) and at last is supplied into conditioned room by air duct 16. At the same time, cooling air flows through valve 23(down) and then into WSHE 7; after being heated and humidified, it passes valve 24(up) and finally is exited to the outdoor by air duct 17.

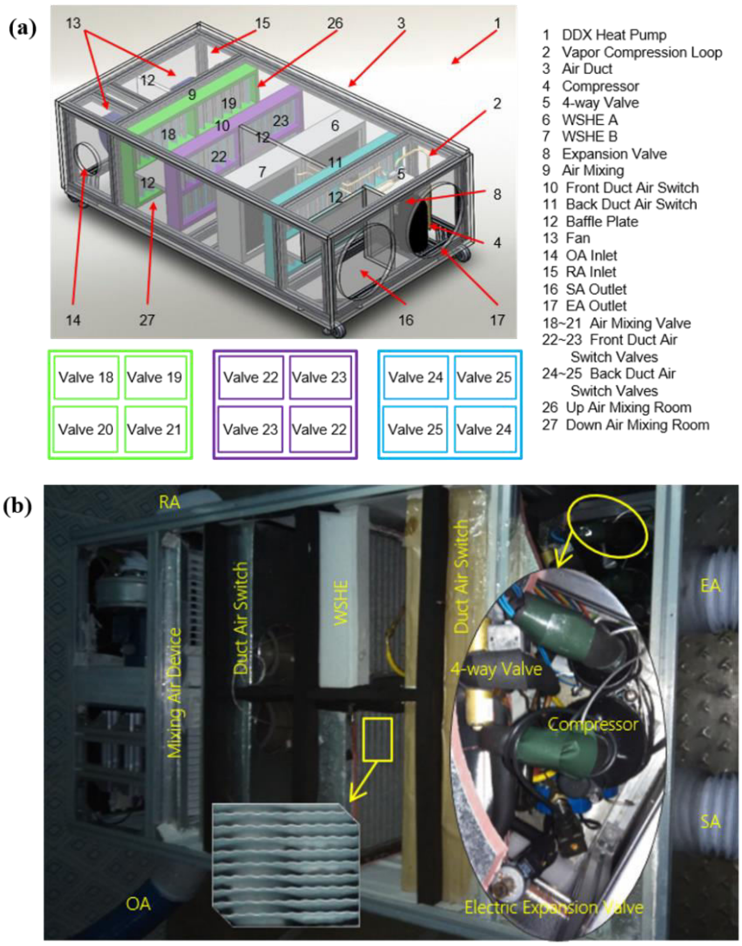


Fig.3. Schematic diagram and photo of the demo DDX HP.

Table 1. Main parts used to construct the demo DDX HP.

| Type | Specifications | Manufacturer | Model |
|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Compressor | Scroll | 1.5HP | GMCC | DA130S1C-20FZ |
| Throttle device | EXV | 500P | Sanhua Group | DPF(Q)2.0C-06-RK |
| 4-way valve | | 2.0HP | Sanhua Group | SHF-9H-34U |

| | | |
|---|---|---|
| Water-sorbing heat exchanger | Outside diameter of copper tube | 9.52mm |
| | Inner diameter of copper tube (smooth tube) | 7.85mm |
| | Tube length | 340mm |
| | Effective tube length | 320mm |
| | Number of tube row | 4 |
| | Number of tube in each row | 12 |
| | Transverse tube pitch | 25.0mm |
| | Longitudinal tube pitch | 21.5mm |
| | Fin pitch | 2.5mm |
| | Fin thickness (plain fin) | 0.15mm |
| | Refrigerant flow path | one in-one out |
| | Airside heat transfer area | $5.72m^2$ |
| | Frontal area | $0.096m^2$ |
| | Base heat exchanger mass | 3.840kg |
| | Desiccant | CSGL |
| | Coated heat exchanger mass | 5.675kg |
| | Desiccant film thickness | ~0.25mm |

### *2.3. Measurements and data acquisition equipment*

Two connected constant temperature and humidity chambers were adopted to simulate various outdoor and indoor air conditions. Each chamber has a space of 3m(length)×3m(width)×2.45m(height), which can supply constant air condition with temperature from -10 to 40°C, ±0.2°C accuracy, and relative humidity from 30% to 90%RH, ±5%RH accuracy. Temperature and humidity ratio of the air are measured by high accuracy and multi-functional digital Thermo/Hygrometer (type: TH110-PNA produced by KIMO Instruments). The measurement range of temperature is 20 to 80°C with accuracy of ±0.2°C and the measurement range of relative humidity is 0~100%RH with accuracy of ±1.7%RH. A thermoelectric anemometer (Kelong-VA40) is adopted to measure the air flow velocity and then the air flow rate can be calculated. Its measurement range and accuracy are 0~50 $ms^{-1}$ and ±0.015$ms^{-1}$. Other temperatures are measured by PT-100 RTD, with an accuracy of ±0.15°C. Suction pressure and discharge pressure of compressor were tracked by a high precision (±0.5%) pressure transmitter (MIK-P300), capable of measuring dynamic change between 0 and 6MPa. A coulomb meter (ZW3415B-RS) facilitates power consumption calculation. It can grasp power data from 0.2W to

10000W with error less than ±0.5%. All the measurement data are collected and transmitted to the recording computer by a data logger (Agilent-34970) with sampling time of 5s.

*2.4. Data reduction*

Criteria of performance evaluation over DDX HP mainly include supply air temperature and humidity ratio and system COP. The calculating equations are listed as below.

$$COP = \overline{Q_a} / \overline{P_{comp}} \tag{1}$$

$$\overline{Q_a} = \rho_a G_a \left( h_{a,in} - \overline{h_{a,out}} \right) \tag{2}$$

Where is the density of moist air, kg/m$^3$, is the air volume flow rate, m$^3$/s, $h_{a,in}$ is the inlet process air enthalpy, J/kg, $\overline{h_{a,out}}$ is the average outlet process air enthalpy, J/kg.

Based on error of sensors, relative uncertainties of $\overline{Q}_a$ and COP calculated from experimental data are ±10.4%, and ±15.0% respectively.

## 3. Results and discussions

*3.1. Performance under typical winter condition*

Outdoor air is kept at 9.5°C, 4.5g/kg, 300m$^3$/h, which will be supplied into the room after being heated and humidified. Indoor air is set at 21°C, 55%RH, and the exhausted air flow rate is 380m$^3$/h, including outdoor air 80m$^3$/h and relief air 300m$^3$/h, whose heat will be extracted and eventually exited into ambient. Working conditions of desiccant heat pump system under winter condition are shown in Fig.4. The evaporation and condensation temperatures will be indicated by the mid temperature of evaporator and condenser where the refrigerant is believed to be in two phase zone. End values for temperature of evaporation and condensation are respectively 4.8°C and 30.6°C.

As shown in Fig.4a, supply air temperature goes down at first due to the thermal inertia of heat exchanger. Meanwhile, humidity ratio of supply air has a conspicuous climb. This is because Water vapour is discharged from desiccant and rejected into the supply air. Then supply air humidity ratio steps down and supply air temperature will slightly rise up, because the effect of water evaporating on condenser temperature becomes smaller. On the whole, supply air is 23.5°C, 14.7g/kg in average, colder but wetter than expected, with value of 23.7°C, 14.3g/kg at end of each cycle.

Energy curves in Fig.4b show that with averaged 4.2kW heating capacity and 0.65kW power consumption by compressor, COP of vapor compression is about 6.5. This high energy efficiency results from two aspects. On one hand, WSHE was free of frost, so vapor compression cycle had no need to defrost, which is helpful to improve evaporation temperature as shown in Fig.4a. On the other hand, DDX HP partly achieved heat recovery from the relief air.

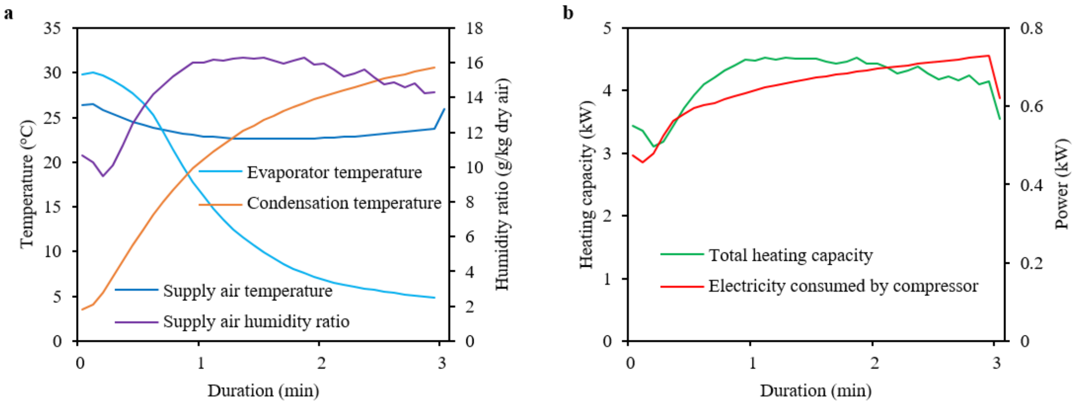


Fig.4. Performance of DDX HP in winter.

### *3.2. Performance under typical summer condition*

The performance of DDX HP in summer has been tested under a common scenario for room air conditioning (outdoor 35 °C/60% RH and indoor 25 °C/50% RH, 30% outdoor fresh air) per standard IOS 5151:1994. Supply air flow rate is 480m$^3$/h and exhaust air flow rate is 490m$^3$/h. The experimental results (Figs. 5a and b) show that the condensation temperature approaches 43°C, the evaporation temperature is approximately 13°C, the average supply air dry bulb temperature is approximately 20°C, the humidity ratio is approximately 8.5g/kg dry air (50% RH), and the power consumed by the compressor and fans are roughly 980 and 149 W, respectively. In other words, the total cooling capacity is 7.0kW with a compressor COP of approximately 7.14 and a system COP of 6.2. These are nearly double the values of current conventional room air conditioners.

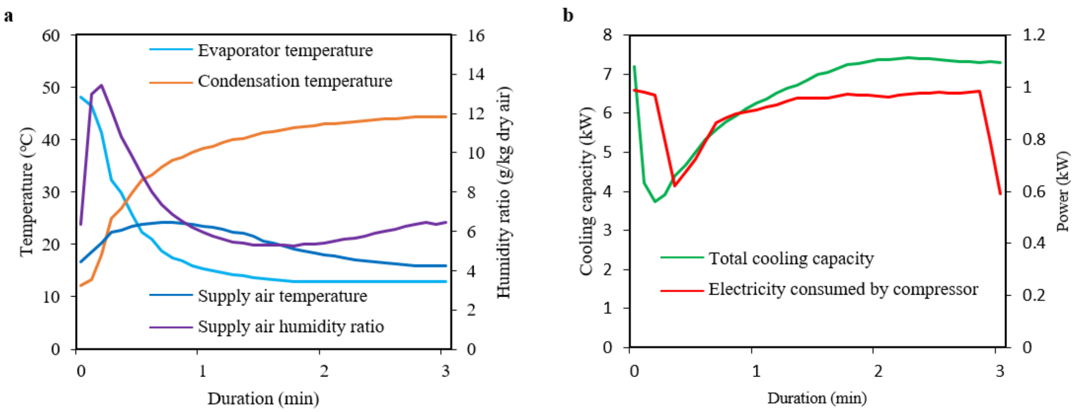


Fig.5. Performance of DDX HP in summer.

### *3.3. Feasibility analysis of solar photovoltaic powered heat pump*

The above results have shown the efficacy of DDX HP towards improving the effectiveness and the energy efficiency for cooling and dehumidification owing to the evaporation temperature rise and the condensation temperature drop. To verify the feasibility of using this new technology to design ZEB, we modelled a house with 250 $m^2$ floor area in Shanghai. Outdoor environmental parameters on August 1 in a Typical Meteorological Year of Shanghai was selected to calculate hourly COP of DDX HP (Fig.6a) and power generation of solar PV models (Fig.6b). The cooling load in the house was modelled with EnergyPlus (Fig.6b). One solar PV model has 260Wp and 15.89% generating efficiency. The rated COP of DDX HP is 6.2 at 35°C, and the real COP at different outdoor temperature was estimated per standard IOS 5151:1994.

The results show that based on DDX HP, one 265Wp PV model can effectively handle the cooling load of about 10$m^2$ floor area in the daytime (7:30~16:00) in Shanghai, which means the modelled house only need 25 PV model. In this case, the total power generation and the power consumed by DDX HP in a whole day could be evaluated (Fig.6c). In current, photovoltaic power generation systems mostly adopt the way of grid to provide electricity. So, the power needed in the night (19:00~5:00) can be provided by grid, while in the daytime it can be largely and even totally provided by solar PV. Considering that the price difference of peak (RMB ¥ 0.917/kWh) and valley electricity (RMB ¥ 0.607/kWh) is considerable, DDX HP powered by PV has a great potential of operation cost saving (Fig.6d). Combined with government subsidies (RMB ¥ 0.82/kWh) and price reduction of PV modules (about RMB ¥ 8/Wp for retail sale), the payback period of solar PV system will be shortened up to 7 years.

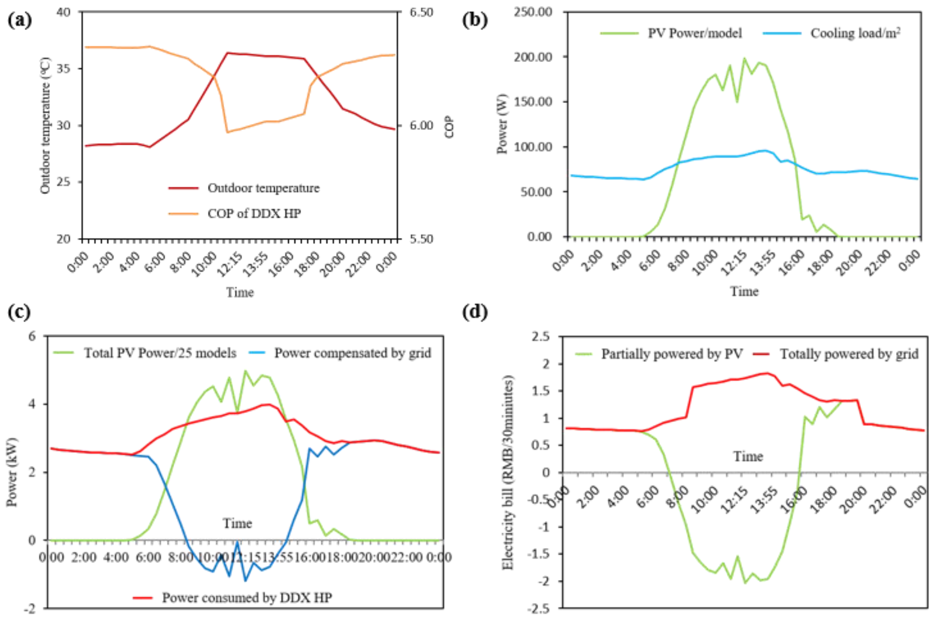


Fig.6. A simple analysis of cost and revenue of solar PV powered DDX HP.

## 4. Conclusions

In summary, efficient cooling and dehumidification, heating and humidification play an important role in building energy conversation, especially for net zero energy building. In this paper, we have analyzed the performance barriers of traditional vapor compression based systems and THIC systems for cooling and dehumidification. Moreover, desiccant-enhanced direct expansion heat pump is proposed so that the air leaving evaporator rightly satisfies the required supply-air. To demonstrate the advantages of this novel approach, a packaged desiccant-enhanced direct expansion heat pump is designed and constructed by replacing the ordinary fin-tube coils within traditional DX A/C with the so-called water-sorbing heat exchangers. Experimental results showed that the system COP was 6.2 under typical summer condition and 5.9 under typical winter condition. According to our limited knowledge, it is the first time that an approach can offer sufficient temperature and humidity control and adequate fresh air ventilation with doubled energy efficiency compared to current room air-conditioners, and most importantly, without sacrificing cost and compactness.

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