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A New Power Storage, Cooling Storage, and Water Production Combined Cycle (PCWCC)

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Oct. 2016

Master Thesis in Energy Systems
15 Credits

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ABSTRACT

Fresh water shortage and hot weather are common challenges in many countries of the world. In the other hand, the air conditioning systems which are used for indoor cooling cause peak electricity demand during high temperatures hours. This peak hour demand is very important since it is more expensive and mainly is supplied by fossil fuel power plants with lower efficiencies compare to base load fossil fuel or renewable owe plants. Moreover, these peak electricity load fossil fuel power plants cause higher green house gas emission and other environmental effects. So, all these show that any solution for these problems could make life better in those countries and all over the world.

In this thesis, a new idea for a Power storage, Cooling storage, and Water production Combined Cycle (PCWCC) is introduced and reviewed. PCWCC is combination of two thermal cycles, Ice Thermal Energy Storage (ITES) and desalination by freezing cycle, which are merged together to make a total solution for fresh water shortage, required cooling, and high peak power demand. ITES is a well known technology for shifting the electricity demand of cooling systems from peak hours to off-peak hours and desalination by freezing is a less known desalination system which is based on the fact that the ice crystals are pure and by freezing raw water and melting resulted ice crystals, pure water will be produced. These two systems have some common processes and equations and this thesis shows that by combining them the resulted PCWCC could be more efficient than each of them.

In this thesis, the thermodynamic equations and efficiencies of each PCWCC sub-systems are analyzed and the resulted data are used in finding thermodynamics of PCWCC itself. Also, by using reMIND software, which uses Cplex to find the best combinations of input/output and related processes, the cost of produced fresh water and cooling from PCWCC is compared with total cost of fresh water and cooling produced by each sub-systems of PCWCC in three sample cities all over the world, Kerman, Dubai, and Texas. These cities are chosen since they have similar ambient temperature trend with different electricity and fresh water tariff's.

The results show that, the PCWCC is economical where there is a significant electricity price difference between ice charging and ice melting hours, off-peak and peak hours, of the day or when the fresh water price is high compare to electricity price. The results also show that how the revenue from fresh water could cover the used electricity cost and make some income as well.

Acknowledgments

First of all, I would like to express my sincere gratitude to Nawzad Mardan, Energy Systems Program Director in university of Gävle, for his consideration and kindness. This thesis and my study program would not be completed without his generous help.

I also would like to appreciate my supervisor, Hans Wigo, for giving me the option to perform the thesis and for his kind help.

Finally, I would like to thanks all teachers and staff of Energy Systems program who gave me and many other students all over the world a chance to follow our master studies in three high rank universities of Sweden and in a modern academic program. During this study program, I received both science and kindness from teachers and staff of Gavle, Uppsala, and KTH universities and I am grateful for it.

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ABBREVIATIONS

Symbol	Description	Unit
CHP	Combined Heat and Power	[-]
COP (β)	Coefficient Of Performance	[-]
CTES	Cold Thermal Energy Storage	[-]
HTF	Heat Transfer Fluid	[-]
FM	Freezing Melting	[-]
HVAC	Heating Ventilation Air Conditioning	[-]
HRSG	Heat Regeneration Steam Generator	[-]
ITES	Ice Thermal Energy Storage	[-]
PCWCC	Power Storage, Cold Storage, and Water Production Combined Cycle	[-]
$Q_{Co,D}$	Extracted heat from building (Cooling Demand)	[kWh]
Q_{Evp}	Absorbed heat by evaporator	[kWh]
RO	Reverse Osmosis	[-]
TES	Thermal Energy Storage	[-]
W_{Com}	Compressor work	[kWh]

INTRODUCTION

Sustainable development, as defined by the World Commission on the Environment and Development (WCED) (1987, p.43), is a development that meets the needs of present generations without compromising the ability of future generations to meet their own needs [1]. By this, the sustainability of a system could be measured as lifetime of a system for generations. In the other words, systems reproduced in more generations are more sustainable ones.

Natural Sustainability

Life in nature exists for millions of years and natural processes are best examples of sustainable systems. By comparing natural processes and artificial ones, human made systems, it is possible to find weak points of human made systems and to make more sustainable and useful ones. As an example, an apple tree could be a good subject to be studied by modern system thinking rates, like; efficiency, rate of production, energy density, and so on. By this study, it is possible to find out why an apple tree was successful to survive during thousands of years.

First, the energy efficiency: the energy efficiency of photosynthesis is very low, it is around 0.5% – 2% for temperate regions, and around 1% - 4% for tropical regions [2]. Then, the rate of wood production, this also is very low and it is around 100MJ of hydrocarbon per year for a sample fast growing apple tree [3]. Finally, the energy density of an apple tree, this also is low and it is less than 6MJ/kg for fresh wood of a sample tree [2]. Not only in energy aspects, but also in other product rates the apple tree's efficiencies and rates are low. An apple tree produces maximum 200kg and 250 kg apple and oxygen per year, respectively, and this means the carbohydrate production rate of 22.8g/h apple and 28.5g/h oxygen for such a big factory (i.e. an apple tree).

The photosynthesis process and the apple tree are only some of examples of the natural processes and other natural processes like food chain, wave energy, and wind energy also are in similar low numbers. It should be noted that, all these rates are not acceptable for common human made energy systems like cars, power plants, factories, and HVAC systems. Now, the question is: why these natural processes survived and won the competition of natural selection (Darwin Theory) and how they become the most sustainable systems of the world but our high efficiency systems in the one hand are emptying the high value fossil fuels and in the other hand are destroying our environment and as a result are not as sustainable as an apple tree.

The answer to above mentioned question is that natural systems use different low value energies and input materials to produces variety of higher value products. They survive and are sustainable since they do not have only one product. They are combination of many low efficiency processes and their total efficiency is high enough to make them the winner of natural selection competition. The apple tree uses free and low density sun shine, abandon carbon dioxide of air, and the minerals and water of dirt and produces food for human and animals, purifies air and soil, provides a good shading and works as an cooler in hot weather condition, slows down rain drops to boost the water absorption by soil, stores energy for many years and has many other benefits. This means that, the sustainable systems are not one purpose simple energy converters but they are good matches of many low efficiency cycles by high overall efficiency.

Although, this good example of sustainability was available around us for many years and inspired researchers and engineers to build new systems, the manmade systems do not seem very sustainable. Actually, the modern systems are using the resources more and more and it seems that the future generations will not have the ability to meet their own needs as our generation had met its needs.

In spite of traditional apple trees, one can consider the modern AC systems. Our generation invented new air conditioning systems which use energy, mostly from fossil fuels, to produce cold weather inside buildings and make life possible in hot climates. This, amongst other fossil fuel consumers, resulted in more energy use and greener house effect and more global temperature increase. Now, to overcome this hot weather, people use more AC systems and again the cycle repeats. This is a positive feed loop and will have negative effects on environment. Figures 1 & 2 show how the temperature and electricity power consumption increased in recent years.

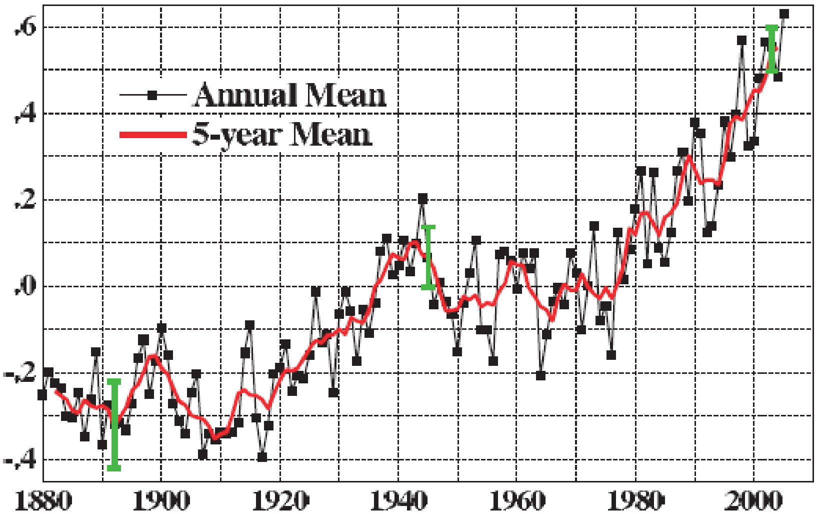


Figure 1: Mean global surface temperature(°C), 1880~2010 [4]

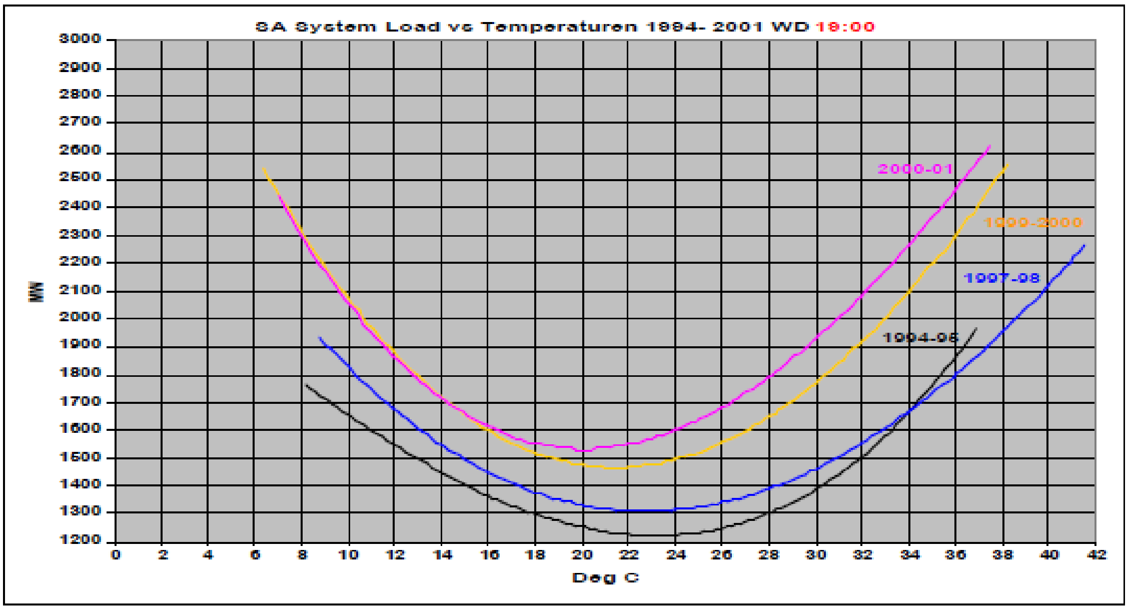


Figure 2: South Australian System Load vs. Temperature, Weekdays at 19:00, 1994-2001 [5]

In figure 2 both low and high temperatures cause more electricity demand, on-peak hours, but, only the high temperature is subject of this study. The curves show that by temperature increase, the electricity demand also increases, on-peak demand, and this grows year by year since more electric devices and equipment are utilized each year.

Moreover, temperature increase leads to more water evaporation and fresh water shortage. To overcome this problem, the desalination plants are used widely in many countries and this also means more fossil fuels and greener house gases and again the

global temperature increase and another positive feed loop. So, it seems that the new high efficiency technologies are not sustainable enough to guarantee the future generations life. In spite of efforts made to make these systems multipurpose and to increase their products, like combining desalination and salt making units [6] or using exhaust hot gas of gas turbine in Combined Heat and Power (CHP) units, the mentioned apple tree is still more sustainable than the AC systems or desalination systems since two later are mainly single purpose systems.
In this thesis, the idea of Power storage, Cold storage, and Water production Combined Cycle (PCWCC) is introduced. PCWCC is a combination of two relatively low efficiency cycles which may be a total solution for some challenges of modern human life like: high peak power, fresh water, and cooling demand as well as waste water disposal problem. This combined cycle consists of two cycles which had been studied separately for many years but are not commercialized for their relatively low efficiencies and high investment costs. These two cycles are ice thermal energy storage and desalination by freezing.

Ice Thermal Energy Storage (ITES)

Ice Thermal Energy Storage (ITES) is one of the Thermal Energy Storage (TES) methods. "TES is a reliable energy management technology that has been in use for over fifty years. TES is an energy management tool that transfers energy use from peak hours to off-peak hours. The positive effect of this is on reducing emissions, lessening the need for more power plants and relieving the stress on transmission and distribution networks" [7].
In this system, the refrigerating system works on off-peak loads during the night and water is frozen storing plenty of latent heat by phase change, and then it is discharged to reduce the load profile of the air conditioning on peak load or partial-peak load during the day [8]. Actually, the ice thermal energy storage, stores the power of electricity by changing water to ice during night hours, when the power prices and environment temperature both are low, and releases it by melting the ice when the power prices and environment temperature both are high. The latent heat of fusion (phase change of water to ice or ice to water) is 334kJ/kg of water. This is a very high thermal capacity and only one ton of ice, nearly one cubic meter of water, is enough for cooling of a middle size house during a hot summer day. So, "in the late 1970's, a few creative engineers began to use thermal ice storage for air conditioning applications. During the 1980's, progressive electric utility companies looked at thermal energy storage as a means to balance their generating load and delay the need for additional peaking power plants. These utility companies offered their customers financial incentives to reduce their energy usage during selected on-peak hours. On-peak electric energy (kWh) and electric demand (kW) costs increased substantially, yet off-peak energy costs remained low" [7].
Figure 3 shows a schematic sketch of sample ITES. In this sketch, the refrigerator freezes water during night hours when the power price and environment temperature is low and produced ice is stored in well isolated ice storage vessel for day time when it is melted by extracting heat from the building.

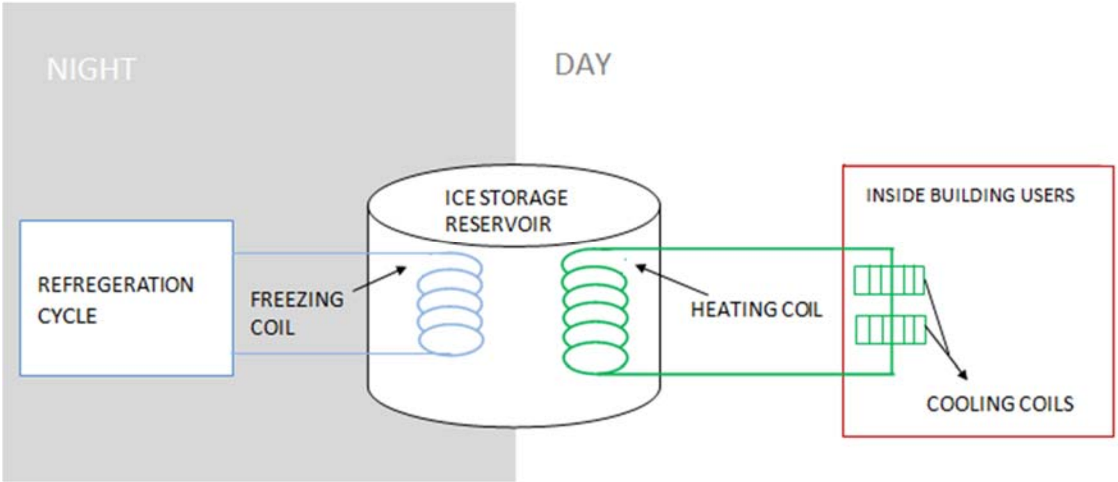


Figure 3: Schematic sketch of power storage by ITES system

AC system using ITES has three main differences compare to single AC systems with same refrigeration cycle. First, the power price is lower during night and it is higher in hot hours of the day. Then, the environment temperature is lower during night and this could increase the efficiency of refrigeration cycle. But the second one should be studied carefully because the working temperature range of the refrigeration cycle in ITES is between environment temperature and the freezing point of water, 0°C literally, but in common compression chillers this is between environment temperature and 15°C ~18°C. So, the advantage or even disadvantage of refrigeration cycle for lower ambient temperature during night hours depends on the temperature differences between ambient temperatures during day and night. Finally, there is some energy saving due to the fact that ITES produces just as much as required cooling load. This electricity reduction is calculated about 11.83% in full storage systems by Sepehr Sannaye and Mohammad Hekmatian [9].

Although, this system consists of only two simple steps: ice formation and ice melting, it still could not compete with single cooling methods like absorption chillers or compression chillers in many countries without help from energy companies or governments. As a result, the commercialized packages of ITES are not common in many countries because their volume per produced cooling is high and their benefit for on-peak hour electricity reduction is not accounted in power prices in many countries. Also, the total thermal efficiency of cold storage is usually lower than the absorption chillers or compression chillers since some of stored cold is wasted in storage hours.

Desalination by Freezing

Another similar cycle to ice storage system, which also works with ice formation and ice melting, is desalination by freezing. Actually, demand for desalination shows increase over the past few years and approximately 70 milion cubic meters of fresh water is produced in 2016 each day around the world. Most of this desalinated water comes from Reverse Osmosis (RO) technologies and thermal desalination systems [10]. Both RO and thermal desalination systems use fussil fuel, as direct energy source or as primary energy source of electricity, and are contributed in carbon dioxide emmission increase and global warming.

In the other hand, the mentioned "Desalination by freezing processes is based on the fact of that ice crystals are made up of essentially pure water. It consists of three discrete steps: ice formation, ice cleaning, and ice melting" [11]. However, this system also could not still compete with available commercial Reverse Osmoses (RO) systems or combined cycle evaporative desalination systems and "desalination by freezing is still

in the form of studies and pilot plant units; attempts at its commercial application have not been successful until now" [11].
The benefit of desalination by freezing is that it does not need feed water of constant chemical contaminates and could be fed by municipal waste water without any expensive and bulky pretreatment system. The freezing desalination is useful because it "has a number of advantages, e.g. low energy requirements, immunity of fouling and corrosion or scaling as well as almost no pre-treatment etc., …" [11]. This is beneficial as RO and other common water treatment systems need many expensive and bulky pre-treatment plants to avoid fouling, corrosion, and scaling.
Although, the desalination by freezing seems more efficient than other common desalination systems, "It requires the separation of the ice crystals from the brine, cleaning of the ice crystals to remove the adhering salts on the crystals surface, and melting of the ice to produce fresh water" [11] and this part of desalination makes it less efficient compare to other desalination systems. Actually, "because of high capital costs, no significant savings in total costs have been anticipated in the production of desalinated water by freezing over other more established methods" [12]. Figure 4 shows a sample schematic diagram of desalination by freezing cycle.

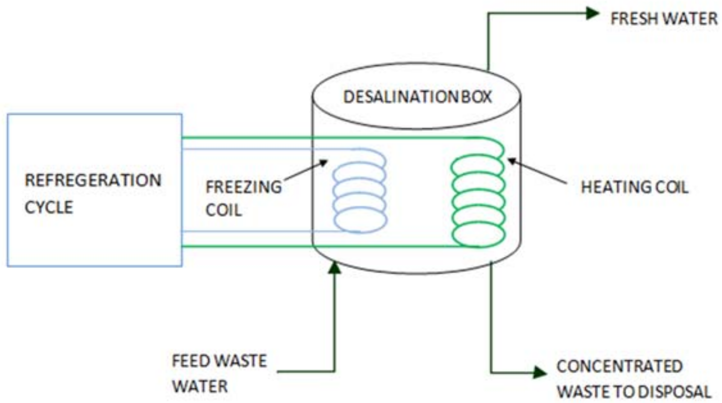


Figure 4: Schematic sketch of desalination by freezing system

It should be noted that the heating coil in this system uses the rejected heat from refrigeration cycle and the condenser is cooled by melting ice. By this, the overall efficiency of systems increases.

Power Storage, Cold Storage, and Water Production Combined Cycle (PCWCC)

Both above mentioned systems are low efficiency and expensive systems compare to commercial AC and water production systems and already are not used in many countries. However, considering the first paragraph, the combination of these two systems may result in a good match of low efficiency systems and make a multipurpose process which stands above other competitors.
From each systems cycle, it is clear that the ITES and freezing desalination have two common steps: ice formation and ice melting and this means that the combination of these two systems needs a few change in both systems and it may increase the total efficiency of the system, like the well-known combined cycle of gas turbine and steam generation plants. Besides, this combined cycle of PCWCC, with almost no need for waste water pre-treatment, could reduce municipal waste water disposal. This means a budget saving which may make this Power storage, Cold storage, and Water production Combined Cycle (PCWCC) a good total solution for many of hot and dry countries all over the world.
Figure 5 shows a schematic diagram of the idea.

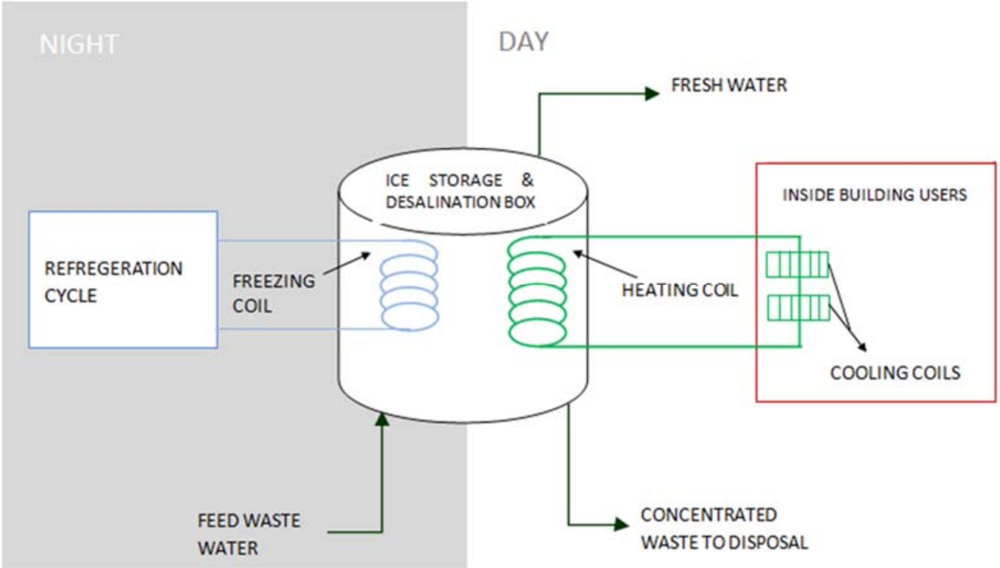


Figure 5: Power Storage, Cold Storage, and Water Production Combined Cycle (PCWCC)

It is clear that, this figure is combination of figure 3 & 4 with small changes. In figure 5, the ITES system is almost unchanged except for ice storage box which is changed to ice storage and desalination box. The desalination by freezing also is changed only in heating coil which uses heat from house instead of heat from refrigeration coil and this may reduce the efficiency of the desalination system compare to a single desalination system, like the back pressure effect of HRSG on gas turbine output which is made up by steam turbine power output; however, it could be neglected in increased overall efficiency.

In next chapters, the basic thermodynamic model of a typical PCWCC will be developed based on the thermodynamic equations and available thermal cycles of two base systems, ITES and desalination by freezing plants. Then, the model will be solved for temperature data of some typical cities all over the world.

For the final part, income evaluation, the reMIND software will be used based on output data of thermodynamic design and available power prices, water prices, and waste water disposal costs in those cities of the thermodynamic model and this will be used to calculate the upper limit of economically acceptable installation cost of a sample PCWCC.

THERMAL ANALYSIS

ITES

ITES is a well known process which is studied by several researchers and its thermodynamic analysis is available in many books and articles. Ibrahim Dincer and Marc A. Rosen had written a book entitled "The Thermal Energy Storage (Systems and Application)" and one chapter of this book is for Cold Thermal Energy Storage (CTES) and ice CTES [13]. Francesco Carducci and Alessandro Romagnoli also showed the ITES application on a building which utilizes a BMS system and they studied the benefits of adding an ITES to existing cooling system [14]. Different types of ITES also are introduced and the thermal equations of each ITES are given by David MacPhee and Ibrahim Dincer [15].

To illustrate the ITES effect on power saving, a typical cooling load demand of a building is given on figure 6. This load demand is for an industrial case which starts from working hours of a day until its end. In this figure, the no storage curve has a pick in the mid day hours and this point in design day, hottest day of year, is the design load of the chiller and for the days other than design day the chiller will work on its partial capacity since the temperature is less than design temperature. By adding full or partial ITES to AC system, the curve of chiller changes and for both storage cases the curve, the design demand of the chiller, will be less than design demand of not storage case and the chiller will work in a more smooth line which means better and more efficient performance.

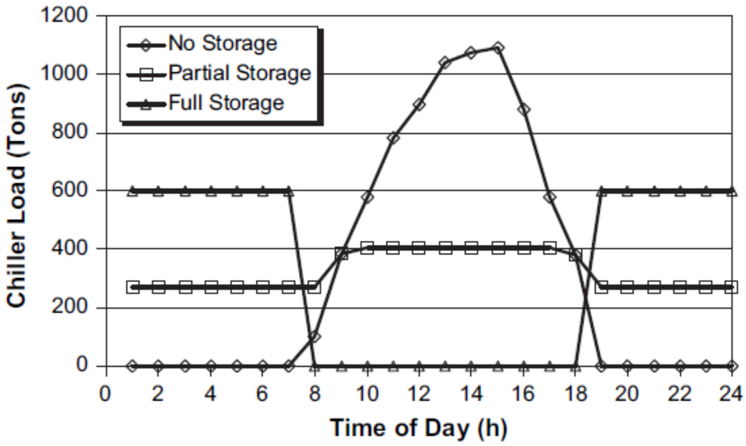


Figure 6: Typical building load (no storage) chilling requirements, as well as partial and full storage requirements [15]

The load profile for home applications is different since there may be a cooling demand during nigh hours as well; however, the basic principle is same. To simplify this study in this thesis, the typical cooling load profile of an industrial building is used, so, there will be no interface between refrigeration working and the ice melting hours and each system could be calculated separately. Also, from partial and full storage cases, the full storage is more useful in PCWCC, as all cooling demand is stored in the ice form and this stored ice will be melted during day hours and this increases the fresh water production rate of PCWCC. These two assumptions are the first and basic assumptions of the study since they are evolved in the effect of hourly ambient temperature and hourly power price effect on the system output.

Another important issue is the way by which the ice is produced in TES system. For refrigeration cycle, the vapor-compression chiller is used in this thesis and this makes is possible to run building cooling system stand alone when the ITES is not available. This refrigeration unit could produce ice either by ice on coil, ice slurries, or encapsulated ice systems which are described in details by David MacPhee and Ibrahim Dincer [15].

Ice on coil is a simple and practical system which is commercialized now and some companies offer it in their ITES solutions for its simple, low cost, and low maintenance benefits. Ice on coil itself is divided in two categories, internal melt and external melt which depend on where the thermal energy is given to ice when it is melting. In both cases, during charging time the sub-cooled brine solution, which could be a refrigerant running in a refrigeration cycle, flows inside tubes immersed in a reservoir of water and the coolant freezes water. In discharge time of internal ice on coil systems, same brine with higher temperature flows inside tubes and gives the heat from air conditioning system to ice and melts it. In discharge time of external ice on coil systems, the ice is melted by blowing air from air conditioning system on coils and by this the air is cooled and the ice is melted. This cycle repeats for a daily operation period, figure 7.
The advantages of the ice on coil system is its easy operation and maintenance and its disadvantages are the high installation cost for the complicated network of tubing and the complicity of using them in partial ice storage loads. Actually, it is very difficult to measure how much ice is formed on coils and this makes it difficult to calculate the stored cold thermal energy when the system it is not working in its full storage capacity.

Figure 7: Photo of ice on coil ITES. In discharge time, ice could be melted by air blowing on coils or by flowing refrigerant media inside tubes [16]

Ice slurries refers to ITES systems which work with a mixture of ice crystals and liquid. The liquid is a solution of water and an antifreeze material, usually ethylene glycol. Like other ITES systems there are variety of ice slurries in different sizes and configuration; however, the most widely applied ice making technology is the scraped surface process which is shown on figure 8. Here, also a typical vapor-compression refrigeration cycle is used. The sub-cooled refrigerant flows inside a tube-in-tube heat exchanger which is insulated on its outer side and filled with mentioned antifreeze brine inside the inner tube. The water content of antifreeze brine freezes in contact with the tube surface and forms crystals on the inner surface of the tube. Then, the rotating scraper lifts up the ice, and the ice is transported to out of heat exchanger with the antifreeze brine.
Although, this seems more complicated than the ice on coils systems, this has some advantages like higher ice storage density as well as good application to any cooling loads without adding more liquid. The higher ice storage density is important since different loads of energy demand could be managed with one system. Less tubing and as a result less sub-cooled refrigerant is another advantage of this system compare to ice on coil systems which also decreases the compressor work in compression-vapor refrigeration cycle. However, this system needs a high amount of energy to drive the

scrapers and it also has more maintenance related costs. But new ice making procedures which are being currently studied may reduce these problems.

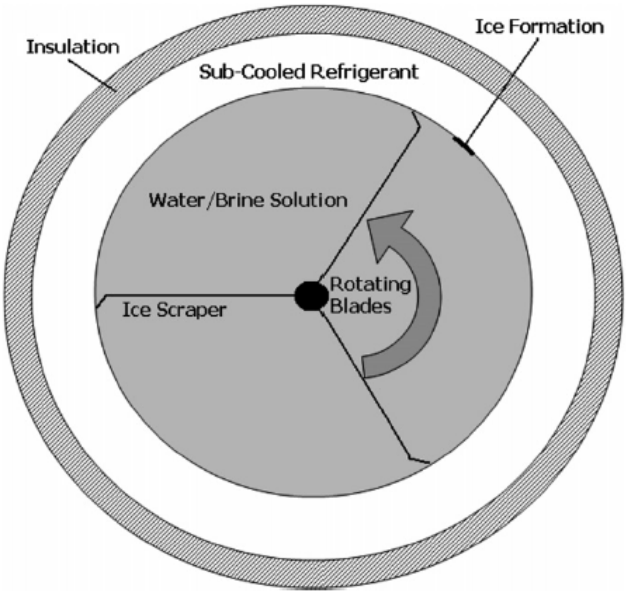
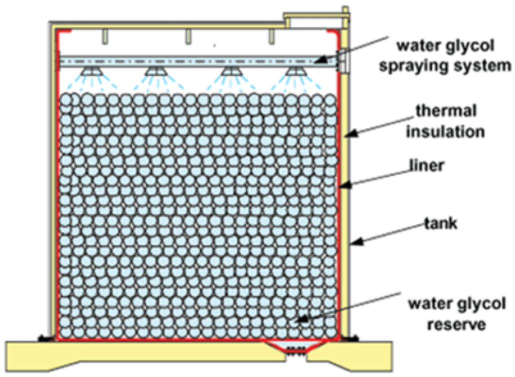


Figure 8: Cross sectional schematic of a scraped surface ice slurry generator [15]

Encapsulated ice is freezing of packed water inside capsules. In this method the water containing capsules, usually spherical shape, are inside a storage tank immersed in a heat transfer liquid. During charging the capsules are cooled until the water inside capsules freezes and during discharging the heat transfer liquid transfers heat from air conditioning system to melt the ice inside capsules.



a B

Figure 9: a) Cross sectional schematic of an encapsulate ice ITES b) Sample of ice reservoir [19]

In mass production case, this system is simple system with the advantage of high heat transfer rate as there will be no ice on coils and the advantage of simple design for variety of sizes of load demands. However, this method needs the development of those capsules technology.

From above mentioned methods, the ice on coil is not suitable for PCWCC since the waste water contamination could be trapped between the ice crystals on coils and it is almost impossible to wash brine from ice. The encapsulated ice definitely could not be used because the capsules are filled once at the factory and they have no advantages for desalination by freezing process. On the other hand, the ice slurries suit the PCWCC and exactly matches desalination by freezing process. As it is mentioned in introduction, the desalination by freezing requires: producing water crystals, separation of the ice crystals from the brine, cleaning of the ice crystals to remove the adhering salts and contaminates on the crystals surface, and melting of the ice to produce fresh water. All these are in good harmony with the ice slurries TES system. In the ice slurries systems, the crystals of water are formed from water and antifreeze solution and then they are transferred from tube-in-tube heat exchanger to the ice storage reservoir. In PCWCC the water antifreeze solution should be replaced by waste water and after transferring ice crystals to storage they should be separated from brine. This is a new idea and it is not exactly clear what would be the challenges of using waste water instead of water and antifreeze solution or the washing ice crystal parts is not known; however, with neglecting those challenges this chapter focuses on the thermodynamic analysis of ice slurry TES system since the result will be used in cost analysis to find out the potential income of a sample PCWCC.

Thermal efficiencies of ITES

To calculate how much electricity is shifted from peak hours to off-peak hours, the scenario of switching between charging and discharging of ice in TES should be specified. This scenario is not unique and it depends on variety of factors like; temperature profile, cooling demand profile, electricity price change in peak hours, expected pay-back time, and so on. However, to simplify this problem, a common scenario is assumed as a basic plan in PCWCC system. According to this assumption, the ITES is employed on an industrial building, no cooling demand during night hours, and the ITES is a full storage type, all cooling demand is stored during night hours and is discharged during working hours of the building. Also, the chiller is vapor compression refrigerator cycle for both ITES case and normal cooling system of the building without ITES.

Since the ITES system itself has some unknown parameters, to simplify the calculations some assumptions are considered as below:

- During charging, the only input to the system will be the compressor work. Other interactions with the ambient atmosphere include heat leakage into the tank, condenser heat transfer to the ambient and energy lost due to inefficiencies in the refrigeration cycle.
- During storage, there is no input to the system; the only interaction with the ambient is heat leakage into the ice storage tank.
- During discharge, the ice storage is used to cool an antifreeze solution. Therefore, the flow difference between inlet and outlet states must be considered, as will be the heat leakage from the ambient atmosphere.
- In terms of specific analysis, the following assumptions are made:

  a) All kinetic and potential effects are neglected.

  b) All piping losses and viscous dissipation losses assumed negligible.

  c) The storage tank is cylindrical, with diameter equal to height.

  d) The thermal energy stored in the Heat Transfer Fluid (HTF) is negligible – all thermal energy is stored in the water/ice medium.

  e) Tank is considered to be of constant temperature, changing according to the specified system process.

  f) The refrigerant used in this process will be R134a, a commonly used material for cooling/refrigeration purposes. The refrigeration cycle will operate between two thermal reservoirs, during discharge time the indoor temperature will be set $20°C$.

  g) All thermo-physical properties are assumed constant at their prescribed values. [15]

Now, the thermal analysis is possible for assumed industrial building when a single vapor compression chiller is utilized, figure 10, or when an ice slurry TES is added to the vapor compression chiller, figure 11.

Thermal equations

For both systems the compressor work, purchased power, is the missing value and although both systems use vapor compression cooling/refrigeration cycle, there are some differences in calculating the compressor work.

Cooling system without ITES

Figure 10 shows the vapor compression cooling system when it is directly used to satisfy the cooling demand of the building.

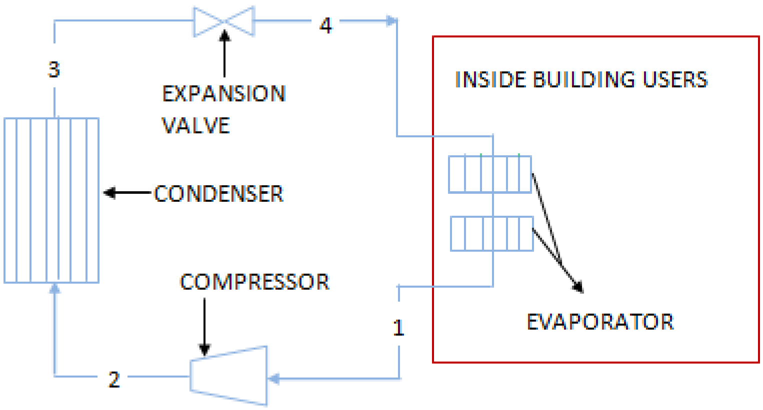


Figure 11: Simple schematic diagram of a vapor-compression cooling cycle

Considering the reference numbers indicated on the flow lines of figure 10, the thermodynamic equations are as below:

The energy balance between the cooling demand and the vapor compression cycle results in the following:

$$Q_{Co,D} = Q_{Evp} \quad (1)$$

According to thermodynamic relations of refrigeration cycles:

$$Q_{Evp} = \beta \times W_{Com} \quad (2)$$

And as a result:

$$Q_{Co.D} = \beta \times W_{Com} \quad (3)$$

Coefficient of performance, β, could be calculated for refrigerant media, R-134a, by having related thermodynamic tables and knowing the hot sink and cold sink temperatures of the refrigeration/cooling cycle. To do this, the thermodynamic cycle of refrigeration/cooling cycle, figure 11, which is solved in basic thermodynamic books, should be solved for each temperature by getting the refrigerant properties from thermodynamic tables. Here, the temperature difference of cooling system without ITES and refrigeration cycle of ITES are important.

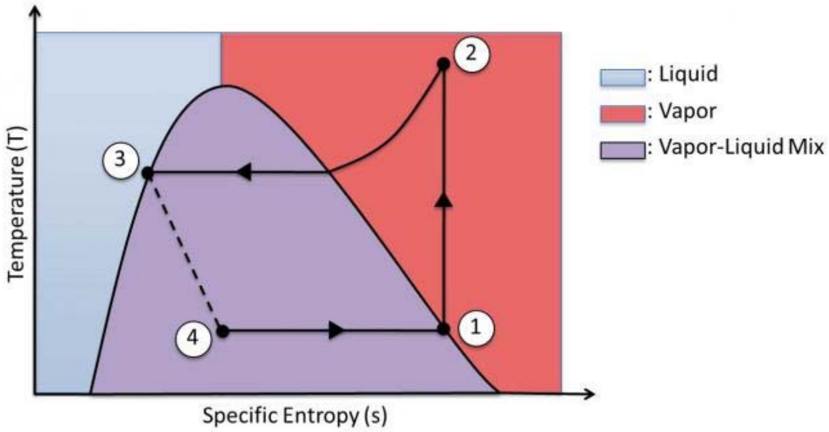


Figure 11: The cooling/refrigeration T-S diagram

In the cooling system without ITES, the temperature of hot sink could be assumed the ambient temperature at the day time plus 10°C since the condenser rejects heat to environment and the optimum temperature difference for heat exchangers input and output fluid design is 10°C. Also, the cold sink temperature is desired indoor temperature minus 10°C for the same reason. The inside temperature is assumed to be 20°C and as a result the cold sink temperature is 10°C. To calculate β, the ambient temperatures, of three typical cities are given in table 1 & 3. These cities are chosen since their electricity prices during peak hours and off-peak hours are available, also, each city represents a different type of temperature profile during 24 hours of a complete day which are shown on figure 12 to 14.

According to figure 12, the ambient temperature in Kerman-Iran, has very hot days but the night is relatively cool and the maximum temperature difference for a 24 hours of a typical summer day is 19°C.

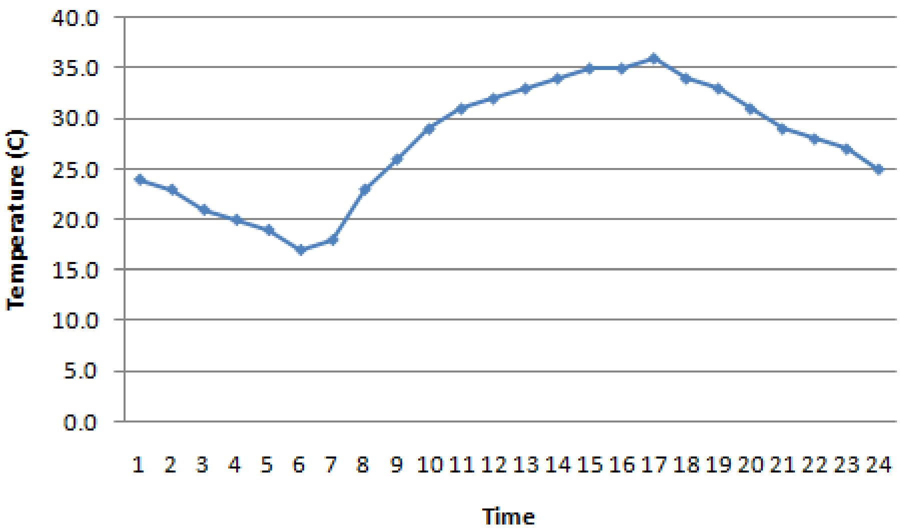


Figure 12: Ambient temperature profile,(°C), for Kerman-Iran city, during a sample summer day

According to figure 12, ambient temperature in Dubai-UAE does not vary too much from day hours to night hours. According to this figure, the temperature level in Dubai is higher than Kerman and as a result the maximum temperature difference for 24 hours of a typical summer day is only 8°C.

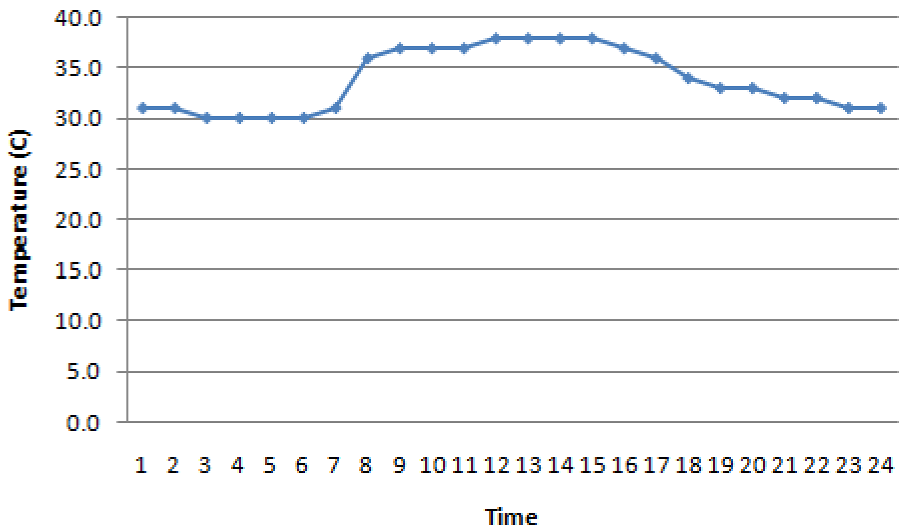


Figure 13: Ambient temperature profile,(°C), for Dubai-UAE city, during a sample summer day

Figure 14 shows the temperature profile of Texas-USA and according to this profile the temperature trend of Texas is similar to Dubai and the temperature does not vary from day to night; however, the temperature levels are lower than Dubai and the maximum temperature difference for a 24 hours of a typical summer day is only $7°C$.

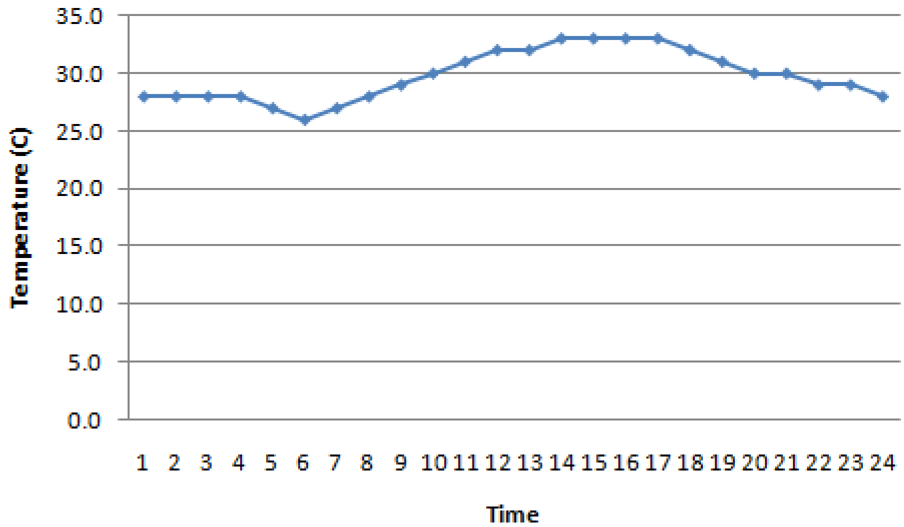


Figure 14: Ambient temperature profile,(°C), for Texas-USA city, during a sample summer day

Table 1: Ambient temperatures,($°C$), for three sample city in working hours of a day

Hour	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
Kerman	23.0	26.0	29.0	31.0	32.0	33.0	34.0	35.0	35.0	36.0	34.0
Dubai	36.0	37.0	37.0	37.0	38.0	38.0	38.0	38.0	37.0	36.0	34.0
Texas	28.0	29.0	30.0	31.0	32.0	32.0	33.0	33.0	33.0	33.0	32.0

Calculation results for β values of evaporative compression cooling system during working hours are given in table 2. It should be noted that the values of β in this table are very high and actually it is impossible to have cooling system with such high COP, this is due to the fact that the temperature differences are low and in this low temperature difference the neglected condenser work or heat transfer losses are comparable with compressor work. However, as these assumptions are for both normal cooling and cooling with ITES systems, the results are useful for compression of two systems which is the aim of this section. It should be noted that, in all tables the working hours are according to a typical working day from 08:00 to 18:00.

Table 2: Coefficient of performance, β, for each in related temperature of table 1

Kerman – Iran											
Hour	8	9	10	11	12	13	14	15	16	17	18
Tcond	33.0	36.0	39.0	41.0	42.0	43.0	44.0	45.0	45.0	46	44
h1	404.2	404.2	404.2	404.2	404.2	404.2	404.2	404.2	404.2	404.2	404.2
h2	419.0	420.6	422.2	423.3	423.8	424.0	425.0	425.5	425.5	426	425
h4	246.2	250.6	255.1	258.1	259.6	261.1	262.6	264.0	264.0	266	263
B	10.7	9.4	8.3	7.7	7.4	7.2	6.8	6.6	6.6	6.3	6.8
Dubai – UAE											
Hour	8	9	10	11	12	13	14	15	16	17	18
Tcond	46.0	47.0	47.0	47.0	48.0	48.0	48.0	48.0	47.0	46	44
h1	404.2	404.2	404.2	404.2	404.2	404.2	404.2	404.2	404.2	404.2	404.2
h2	426.1	426.3	426.3	426.3	427.0	427.0	427.0	427.0	426.3	426	425
h4	265.7	267.2	267.2	267.2	268.7	268.7	268.7	268.7	267.2	266	263
B	6.3	6.2	6.2	6.2	6.0	6.0	6.0	6.0	6.2	6.3	6.8
Texas – USA											
Hour	8	9	10	11	12	13	14	15	16	17	18
Tcond	38.0	39.0	40.0	41.0	42.0	42.0	43.0	43.0	43.0	43	42
h1	404.2	404.2	404.2	404.2	404.2	404.2	404.2	404.2	404.2	404.2	404.2
h2	420.1	422.2	422.0	423.3	423.8	423.8	424.0	424.0	424.0	424	424
h4	250.6	255.1	256.4	258.1	259.6	259.6	261.1	261.1	261.1	261	260
B	9.7	8.3	8.3	7.7	7.4	7.4	7.2	7.2	7.2	7.2	7.4

Now, according to equation 3 it is possible to calculate compressor work by dividing cooling demand by β or $W_{Com} = Q_{Co.D} / \beta$.

Cooling system with ITES

Figure 15 shows the vapor compression refrigeration system when it is combined by full capacity ITES system and satisfying the cooling demand of an industrial building.

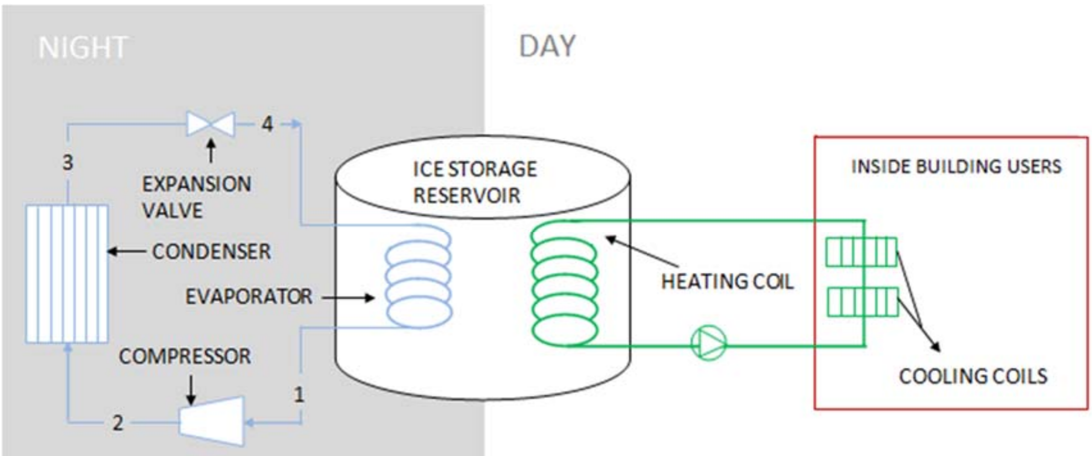


Figure 15: Simple schematic diagram of a cooling cycle with full storage ITES

Considering the reference numbers indicated on the flow lines, the thermodynamic equations could be written as below:

The energy balance between the cooling demand and the vapor compression cycle results in the following:

$$Q_{Co,D} + Q_W = Q_{Evp} \quad (4)$$

In which $Q_{Co,D}$ and $Q_{Evp}$are similar to equation number (1), but the Q_W represents the heat loss from ice storage during charge and discharge time and as we have full storage capacity and the required ice is stored during non-demand hours, then, the Q_W is for a whole day. Actually, this is a conservative assumption since there may not be considerable waste heat from ice storage reservoir during start of charging and at the end of discharging.

According to thermodynamic relations of refrigeration cycles:

$$Q_{Evp} = \beta \times W_{Com} \quad (5)$$

And as a result:

$$Q_{Co.D} + Q_W = \beta \times W_{Com} \quad (6)$$

Now, the coefficient of performance, β, could also be calculated for the same refrigerant media, R-134a, by having related thermodynamic tables, but here the hot sink and the cold sink temperatures of the refrigeration/cooling cycle are different.

In this case, the hot sink temperature is ambient temperature but in night hours, table 3, and the cold sink temperature is the working temperature of ice slurries system, $-12°C$ according to David MacPhee, Ibrahim Dincer [15]. By evaporator temperature and the temperatures of table 3, the values of β are calculated and are given in table 4.

Table 3: ambient temperatures, ($°C$), of three sample city in night hours of a day

Hour	19	20	21	22	23	24	01	02	03	04	05	06	07
Kerman	33.0	31.0	29.0	28.0	27.0	25.0	24.0	23.0	21.0	20.0	19.0	17.0	18.0
Dubai	33.0	33.0	32.0	32.0	31.0	31.0	31.0	31.0	30.0	30.0	30.0	30.0	31.0
Texas	31.0	30.0	30.0	29.0	29.0	28.0	28.0	28.0	28.0	28.0	27.0	26.0	27.0

The calculation results for β values of evaporative compression cooling system during night hours are given in table 4. In this table, the night hours, ice charging time, are from 19:00 to 07:00.

By β values of table 4, only Q_W, the heat loss from ice storage during charge and discharge time, is required to calculate the compressor work. According to David MacPhee and Ibrahim Dincer [15], the Q_W is maximum 1% of total produced ice during charging and discharging time. Therefore, the compressor work is

$$Q_{Co.D} + \left(\frac{1}{100}\right)Q_{Co.D} = \beta \times W_{Com}$$

And as a result:

$$W_{Com} = 1.01 Q_{Co.D}/\beta \quad (7)$$

Table 4: Coefficient of performance, β, for each city in related temperature of table 3

						Kerman – Iran							
Hour	19	20	21	22	23	24	1	2	3	4	5	6	7
Tcond	43.0	41.0	39.0	38.0	37.0	35.0	34.0	33.0	31.0	30.0	29.0	27.0	28.0
h1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1
h2	428.0	427.0	426.0	425.0	425.0	424.0	423.0	422.0	421.0	421.0	420.0	419.0	419.0
h4	261.1	258.0	255.1	253.6	252.1	246.2	247.6	246.0	243.3	242.0	240.4	237.5	238.9
β	3.5	3.7	3.9	4.1	4.1	4.4	4.5	4.7	4.9	5.0	5.2	5.5	5.5
						Dubai–UAE							
Hour	19	20	21	22	23	24	1	2	3	4	5	6	7
Tcond	43.0	43.0	42.0	42.0	41.0	41.0	41.0	41.0	40.0	40.0	40.0	40.0	41.0
h1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1
h2	428.0	428.0	427.4	427.4	427.0	427.0	427.0	427.0	426.1	426.1	426.1	426.1	427.0
h4	261.1	261.1	259.5	259.5	258.0	258.0	258.0	258.0	256.4	256.4	256.4	256.4	258.0
β	3.5	3.5	3.6	3.6	3.7	3.7	3.7	3.7	3.8	3.8	3.8	3.8	3.7
						Texas–USA							
Hour	19	20	21	22	23	24	1	2	3	4	5	6	7
Tcond	41.0	40.0	40.0	39.0	39.0	38.0	38.0	38.0	38.0	38.0	37.0	36.0	37.0
h1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1	391.1
h2	427.0	426.1	426.1	426.0	426.0	425.0	425.0	425.0	425.0	425.0	425.0	425.3	425.0
h4	258.0	256.4	256.4	255.1	255.1	253.6	253.6	253.6	253.6	253.6	252.1	253.6	252.1
β	3.7	3.8	3.8	3.9	3.9	4.1	4.1	4.1	4.1	4.1	4.1		4.1

Desalination by Freezing

Desalination by freezing process, which is called Freezing-Melting (FM) process as well, is a fresh water production method which similar to desalination by vaporization is based on phase change. Unlike to reverse osmosis and electrolysis desalination process in which the state of water does not change, in desalination by freezing and desalination by vaporization, the state of sea/waste water changes from liquid state to solid/gas state and then by melting/condensing process pure water is produced.

Although the desalination by freezing is still only in prototype units, the desalination by vaporization is already commercialized and the good combination of gas turbine with vaporization desalination is very common in many countries especially in Persian Gulf region. However, the freezing desalination has some advantages to vaporization and "perhaps the greatest potential advantage of desalination by freezing is the very low energy requirement compared to that of the distillation [by vaporization] processes. The reduction in energy costs results because the latent heat of fusion of ice is only one seventh the latent heat of vaporization of water. FM (Freezing-Melting) separation could save 75 to 90% of the energy required by the conventional thermal process." [17] This is the main advantages which are referred in many articles and perhaps is the first encouraging aspect for many researchers and investigators to start working in this field. Mohammad Shafiur Rahman et al. [17] also added some more benefits of desalination by freezing like: low operating temperature and as a result lower scaling and corrosion problems as well as inexpensive or low cost materials like plastic and other non-metallic materials. Besides, the high surface area and high heat transfer coefficient can be achieved with direct contact freezing method. As it is mentioned in the introduction, the general absence of pretreatment is another advantage which results in less chemical requirement and being less sensitive to fouling and contaminant of solution and as a result, the desalination by freezing has less ecological impact.

In the other hand, the disadvantages of freezing desalination compared to evaporation desalination and reverse osmoses made it uneconomical until now. Some of these disadvantages are: (a) higher initial investment and capital costs and higher maintenance and operation costs, (b) the undesirable flavors and aromas that may remain in produced fresh water, (c) need for mechanical compressors which are expensive and have high electricity demand, (d) the high-quality energy, electricity, is needed for freezing compared to low quality energy, hot gas, used in many evaporation processes, (e) lack of technology/knowledge in freezing and ice crystal washing field compared to higher available technology/knowledge in steam and evaporation field [18].
In suggested PCWCC, disadvantages a, and c are not disadvantages any more as they are part of the ITES system and there is no need for investment. Also, item d is not relevant because the ITES system already uses that high value energy, electricity, to produce cooling and PCWCC reuses the waste cold of ice in the ITES system, similar to vaporization desalination from waste hot gases from gas turbine. Hence, some disadvantages of the freezing desalination are not important and other ones should be checked one by one in its related field.
Freezing desalination has three discrete steps: ice formation, ice cleaning, and ice melting and each step is more detailed in following sections.

Ice formation
Ice formation or freezing is the first stage and there are varieties of methods to do so and table 5 addresses most common methods which are studied in some articles.

Table 5: A possible classification of freezing processes [18]

A. Direct contact freezing
B. Indirect contact freezing
a. Internally cooled
1. Static layer growth system
2. Layer crystallization unit on rotating drum
3. Progressive crystallization unit
4. Dynamic layer growth system
5. Suspension crystallization
b. Externally cooled
1. Super-cooled feed
2. Ripening vessels
C. Vacuum freezing

In the item A of the table 5, direct contact freezing, the refrigerant in its liquid state is sprayed into sea/waste brine and boils inside it getting heat from brine. This makes crystals of ice which by buoyancy force go upward and accumulate at the top of brine, figure 16. Then, the refrigerant vapor is extracted to the compressor and the ice-brine slurry is taken to ice washing column, next step. This is the most efficient freezing method since there is no thermal resistance between refrigerant and brine; however, there are many limitations and above all is that the common compressors could not compress the refrigerant mixed with water vapor. In the other hand, the possible migration of refrigerant vapor to ice-brine solution wastes the refrigerant and continues charge of refrigerant will be required. Also, in the ITES systems, it is preferred to be able to use refrigeration cycle for supplying cooling demand in day hours, when the ice storage is not sufficient, and in this case it is very complicated to couple the direct contact freezing with the AC system.

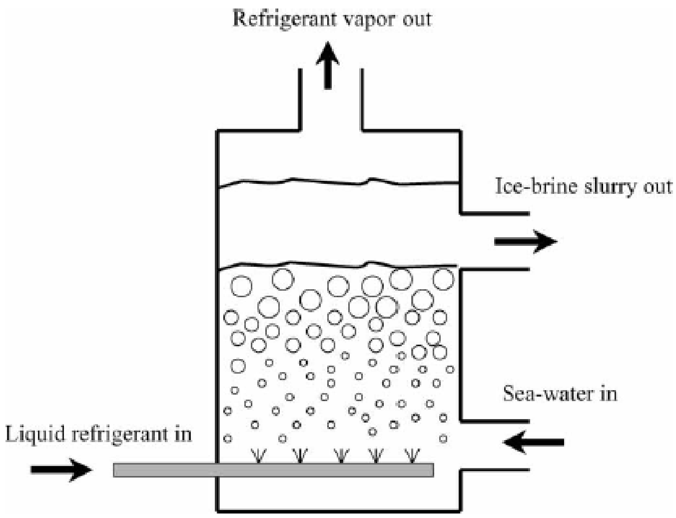


Figure 16: Schematic diagram of direct freezing unit [18]

In the item B of table 5, indirect contact freezing, the refrigerant does not contact directly with brine and instead of that, the refrigerant goes through heat exchanger tubes/plates and the heat transfer is from wall of those tubes/plates. It is clear that, in all of indirect contact methods of table 5, the separation of ice crystals from heat exchanger tubes/plates is an important challenge and as it is mentioned in introduction, this challenge is solved by the only choice for PCWCC freezing, the indirect freezing by ice slurry. Figure 17 shows a schematic diagram of an indirect freezing desalination unit.

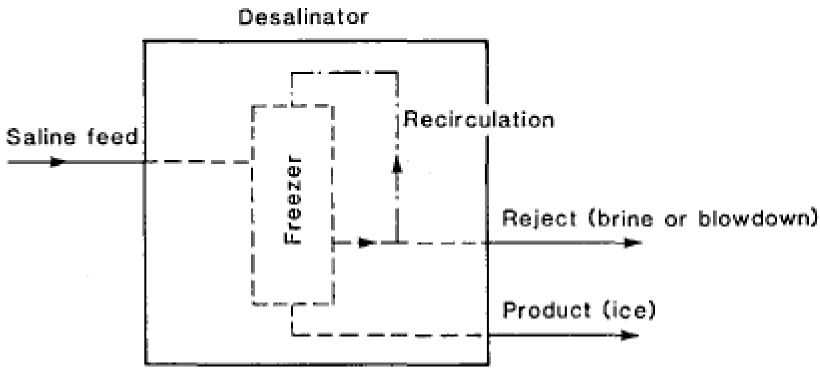


Figure 17: Schematic diagram of indirect freezing desalination unit [12]

Indirect freezing process has some disadvantages compare to direct freezing process. First, the energy requirement is relatively higher due to the resistance of the surfaces, high metallic heat transfer surfaces are required and the equipment is complex, expensive and difficult to operate and maintain compare to direct contact freezing. Therefore, the direct freezing is more utilized in desalination [18]. However, mentioned disadvantages are covered by utilizing the available equipment of common ITES systems.

Regarding thermal calculation, there is no need for other thermal calculation for ice formation as it is part of the ice slurry TES system and it is discussed before.

Ice separation

Before the ice crystals can be melted, they must be separated from brine and effective separation of crystals and washing them is very important to have pure water. This separation is categorized as: presses, gravity drainage, centrifuges, and filters. The separation itself happens in wash columns. There are two types of wash columns, gravity and pressurized. In pressurized wash columns, the crystals at the top of column are washed by pressurized wash liquid, part of melted pure crystals. Water washes impurities from the surface of the crystals and its pressure also sends the concentrate through a filter at the bottom of the column and by this there is no contact between brine and the crystals. In gravity wash column, simpler than pressurized column, the column is larges with higher height as the required pressure is driven from elevation difference between top and bottom of. In these columns, the ice crystals move upward by their own buoyancy force and at the top of column they go through wash water and the brine is cleaned from crystals surfaces. From pressurized and gravity wash columns, the gravity wash column uses almost no electricity for pressurizing water; however, it is not economical in freezing desalinations as the crystals flow is limited by the buoyancy (or gravity) forces. And this makes it very slow to be used in common freezing desalination units.

Although, both pressurize and gravity columns could be used in PCWCC, again, it seems that the gravity columns are more useful in PCWCC since it has less power consumption. The slow rate of crystal washing is not very important as the wash column can use the extra discharging time when no new ice crystals are formed, during working hours of the day. Using gravity wash column, the electricity of ice separation is limited to wash water pump work which could be neglected.

It should be noted that according to Shafiur Rahman et al., the wash water consumption in wash column is about 2% which is supplied from melted water [18]. This 2% will be used later in calculation of fresh water production rate.

Ice melting

After washing crystals, they should be melted in melting units to produce fresh water. Although, this stage seems straight forward, it is more complex in freezing desalination since in the freezing desalination, the cooling capacity of crystals is used to cool the refrigerant condenser to increase the overall efficiency. However, this is not the case in PCWCC because the washed crystals are stored in ice storage reservoir and are then melted by hot supply water from building cooling coils to satisfy the cooling demand of the building. Here, a heat exchanger is needed which is already part of the ITES system. So, the ice melting process in PCWCC is the melting process of ITES and again there is no need for extra thermal analysis for it.

A complete freezing desalination unit

Figure 18 shows the complete indirect freezing desalination process diagram. In this process the feed water passes though a heat exchanger which uses the cooling capacity of rejected brine and melted ice to cool the feed water, increasing the overall efficiency. Then it is cooled until the ice crystals are formed and then this ice and brine slurry is pumped to wash column and there the ice and brine is separated. Brine goes to mentioned feed water initial heat exchanger and the ice is transferred to melting unit. In melting unit, the ice is melted by heat from refrigeration cycle condenser. Small part of this melted ice, 2%, is transferred back to wash column and is used to wash the ice crystals and remaining part, purified water, goes through the feed water initial heat exchanger.

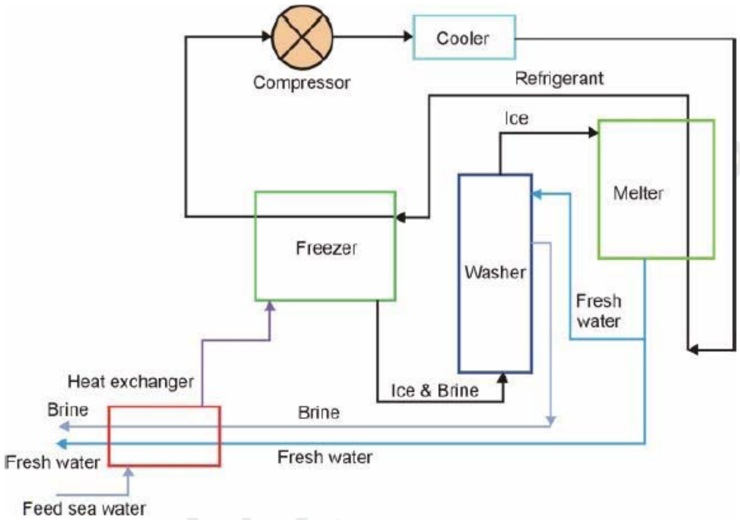


Figure 18: An indirect freezing desalination process [11]

Power Storage, Cooling Storage, Water Production Combined Cycle, PCWCC

PCWCC is a combination of ITES and freezing desalination systems and now it is possible to design the PCWCC process flow diagram by putting above mentioned parts together and removing the duplicated or useless parts. From the ITES cycle, figure 15, all parts are required in PCWCC but some parts of freezing desalination should be decided if are needed/useful in PCWCC or not. These parts are the inlet feed water heat exchanger and the ice melting by condenser unit. It is clear that the second one, condensing refrigerant by melting ice, is out of PCWCC as the ice is produced and stored during night hours when the condenser is working and is melted during working hours when there is no need for compressor work, also this is in contrast with ITES design purpose to use the stored ice for condenser cooling. So, this part of freezing desalination should be modified to a common air cooler of ITES systems.

Inlet feed water heat exchanger has two entering streams: one is purified water and the one is concentrated brine. According to Shafiur Rahman et al. [18], in case of sea water, only 15% of inlet feed water can be purified to fresh water and 85% of inlet feed water becomes concentrated brine and should be disposed. As the mentioned 85% concentrated brine is near zero, it has a high cooling potential and should be used in the PCWCC as well. However, the remaining 15% of inlet feed water, purified waste water, is not useful as its temperature is higher, near indoor set temperature, and removing it from the feed water initial heat exchanger does not have any effect on overall efficiency of the system, so, the final conceptual process diagram of PCWCC is shown on fig. 20.

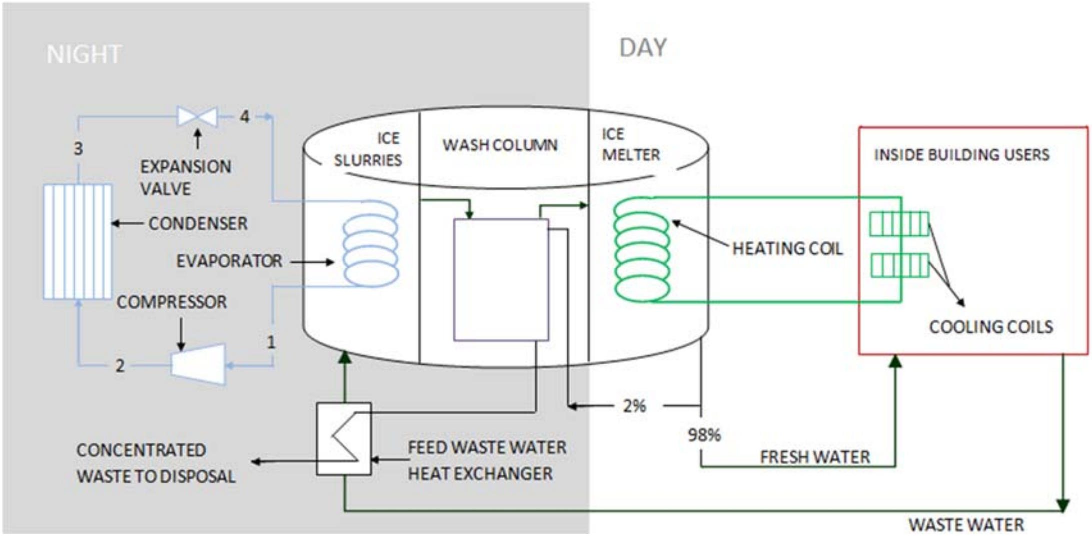


Figure 19: Schematic diagram of complete PCWCC

Thermal analysis of PCWCC

To simplify the calculations of PCWCC, some assumption are required as below. It should be noted that some of these assumptions are from Thermal Efficiencies of ITES section and some are for freezing desalination parts which discussed in above sections.

- During charging the only input to the system will be the compressor work. Other interactions with the ambient atmosphere include heat leakage into the tank, condenser heat transfer to the ambient and energy lost due to inefficiencies in the refrigeration cycle.
- During storage, there is no input to the system; the only interaction with the ambient is heat leakage into the ice storage tank.
- During discharge, the ice storage is used to cool an antifreeze solution. Therefore, the flow difference between inlet and outlet states must be considered, as will be the heat leakage from the ambient atmosphere.
- In terms of specific analysis, the following assumptions are made:

  a) All kinetic and potential effects are neglected.

  b) All piping losses and viscous dissipation losses assumed negligible.

  c) The storage tank is cylindrical, with diameter equal to height.

  d) The thermal energy stored in the HTF is negligible – all thermal energy is stored in the water/ice medium.

  e) Tank is considered to be of constant temperature, changing according to the specified system process.

  f) The refrigerant used in this process will be R134a,a commonly used material for cooling/refrigeration purposes. The refrigeration cycle will operate between two thermal reservoirs, during discharge time the indoor temperature will be set $20°C$.

  g) All thermo-physical properties are assumed constant at their prescribed values.

- The scenario of switching between charging and discharging of ice is same as scenario of ITES system.
- Similar to ITES system, the chiller is vapor compression refrigerator cycle.

Considering above mentioned assumptions and the relative calculations of simple cooling system and combined cooling and ITES system, the thermal analysis is possible for assumed industrial building when a PCWCC is utilized, figure 6.

As the wash column is considered to be gravity type, and the ice slurries TES, which thermodynamically solved in previous section, is used for ice crystallization system, the missing factor, the compressor work, is similar to ITES system and it could be written as equation 7:

$W_{Com} = 1.01 Q_{Co.D}/\beta$

The β values were given in table 4.

This is the final step in thermodynamic analysis of PCWCC and the evaluation of β values negative effect and peak-power price positive effect on total price of purchased power as well as the income from produced fresh water per kilowatt of cooling demand will be discussed in next section.

WATER TREATMENT AND FRESH WATER RATES

Produced fresh water comes from melted ice and by calculating the required ice the fresh water also is available. The latent heat of fusion (phase change of water to ice or ice to water) is 334kJ/kg of water, so, by knowing the cooling demand and as a result the stored ice, it is possible to calculate the produced ice. To make it simple, the stored ice could be calculated per kWh of cooling demand as per below:

kWh = 1kJ x 3600 s
Stored ice [kg] = (Cooling demand) / (334kJ)
Stored ice per kWh of cooling demand = 3600 / 334 = 10.8 kg/kWh

When the ice is melted, 2% of produced water is used for washing ice. Hence, the fresh water per kWh of cooling demand is:

Produced fresh water per kWh of cooling demand = 10.8 x (1- 0.02) = 10.584 kg.
This 10.584 kJ/(kWh cooling demand) is one of the input data for reMIND fresh water calculation equation.

PCWCC reMIND MODELING

Introduction

In this chapter the results of thermal analysis and fresh water production calculation from previous chapters are used to model a PCWCC and compare it with the models of its sub-systems and this modeling is done by reMIND software. ReMIND modeling software, as a user friendly and practical software, by using Cplex finds the best combinations of input/output and related processes to minimize the cost of system. reMIND output results contain capital cost and quantity of each defined flow in related time steps. It should be mentioned that in this project inflow and outflow efficiencies are assumed to be 100% and this does not affect the results as these efficiencies are assumptions of thermodynamic models. The ice storage efficiency is 98% in both ITES and PCWCC as it is mentioned in previous chapter. Also, regarding internal changes, the modeling is done for 24 time steps, the time steps of a full day, and this means that both temperature hourly variation and power price hourly variation are considered in the models. Furthermore, modeling is done for different scenarios from unlimited capacity PCWCC and ITES to more realistic, limited capacity PCWCC and ITES. Finally, one scenario is considered for selling surplus fresh water from PCWCC, if any, to show the income of water treatment by PCWCC when there is no need for cooling demand.
As we had three cities in our thermodynamic model, in this chapter also these three cities, Kerman, Dubai, and Texas, are modeled according to their electricity and water tariffs.

Aim

First aim is to study the revenue from PCWCC compare to evaporative chiller and ITES and to see if the variable electricity tariff effects the operation time of both ITES and PCWCC or not. By this, it is possible to find out the maximum revenue from PCWCC in different cases which could be used to find out the payback time of PCWCC and ITES systems. As it is possible to store extra fresh water from PCWCC, final aim is calculating the revenue from using extra capacity of PCWCC to produce fresh water even if the cooling is not required.

Method

The modeling has been carried out based on the data from previous chapters and the water and electricity prices of the modeled cities. This modeling is done by MIND method which optimizes the industrial energy systems by describing all relations and limitations in an equation matrix. The input data for this method is mainly fuel, (electricity in this case) & material as well as demanded production (cooling and water in this case) or price. Used software is reMIND which based on MIND method minimizes costs for fuel, electricity and investments. ReMIND first compiles the model in an equation matrix and the matrix is optimized by CPLEX. The final output is the most cost-effective combination of parts and production rates.

Result and Analysis (Part A)

This modeling is carried out for each city in three different scenarios as follows:

Case a: this is the basic simulation of the system. In this scenario all three cooling systems, evaporative chiller, ITES, and PCWCC are connected to the cooling demand and could supply the required cooling demand with no limitation. In this scenario, the ITES and PCWCC have unlimited ice production and storage capacity. The water demand is considered equal to 100 cubic meters for this scenario and two other scenarios. In this scenario, the only limiting boundaries for all systems are the cooling demand and water demand.

As the β, coefficient of performance, is time dependent and varies for each hour of a day, the model should be dynamic model with 24 steps. The total time for the scenario is 24 hours and it starts from hour 19:00 since the ITES and PCWCC should be charged during night hours and used next day for cooling of the building.

Case b: this scenario is similar to scenario "a" except for the ice production capacity of ITES and PCWCC. The capacities of these two systems are limited such that in the Kerman city, the only city in which electricity price varies during a day, required ice could be produced in low electricity prices of the night hours. This is more realistic as the systems in real condition work in their design capacity not in unlimited capacity.

Case c: in the scenarios "a" & "b", the fresh water demand is considered in calculations for 100 cubic meters. However, the revenue from surplus water, if there is any extra water production capacity, is not considered in calculations. In this scenario, the surplus water is stored and sold according to fresh water price of each city.

It should be mentioned that the cooling demand profile in all cases are considered according to the figure 6 which shows a typical cooling demand of an industrial building and the water demand is roughly considered as 100 cubic meters.

The schematic reMIND model of final task is shown in figure 20.

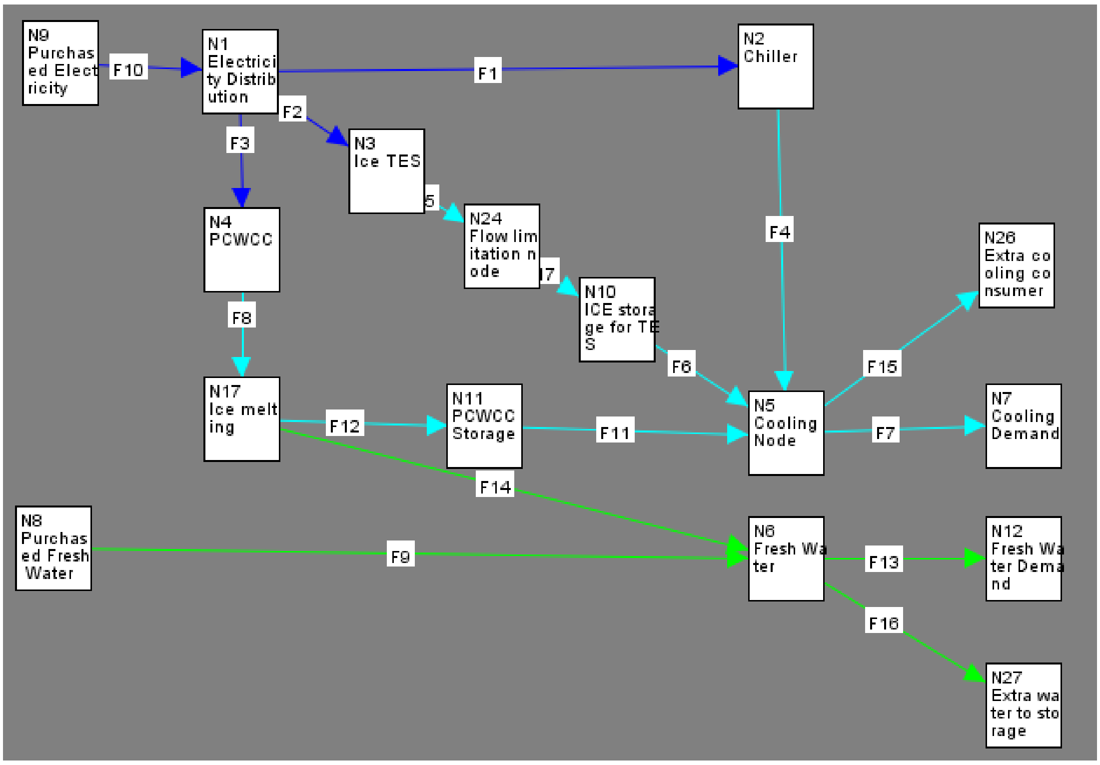


Figure 20: Schematic of final model in reMIND. Each line represents a flow, blue is electricity, cyan is cooling, green is fresh water

In figure 20 the node N9 is the electricity supply point and the electricity prices are defined in this node. The purchased electricity is distributed via N1 to all three expected users without any limitations. N2, N3, and N4 are representative of the temperature changes on each system. Actually, these nodes simulated the β, coefficient of performance, for evaporative chiller, ITES, and PCWCC respectively. As a result, the ITES and PCWCC can produce ice from 19:00~07:59 and the evaporative cooler working hour is limited to 08:00~19:59. N24 & N17 are added to the case "a" model to restrict the ice production capacity of the ITES and PCWCC. However, the water production of PCWCC also is taken from N17. N10 and N11 are ice storage nodes.
N8 is defined to simulate the water cost. It should be note that in all three cases, the 100 cubic meters water is the demand and there is no limitation for extra water production. However, only in case "c" N13 is added to simulate the revenue from surplus water. Besides, N7 and N12 are destination nodes for cooling and water demands respectively. Finally, N26 and N27 are destination nodes for extra cooling and water respectively.

Dubai

According to the figure 13 of thermal analysis chapter, in a typical summer day of Dubai, the ambient temperature in the Dubai-UAE does not vary too much from day hours to night hours and the maximum temperature difference for 24 hours of a typical summer day is only 8°C. This date is simulated by β value. For other inputs, the electricity price in these cities constant during all 24 hours and does not vary in peak hours. Actually, it is depended on monthly consumption only. For this study, the industrial building, the electricity price is 0.0625$ for less than 10000kWh power consumption and 0.103$/kWh for more power consumption, with US dollar change rate: 1US$=3.68Dh. Finally, the fresh water price varies with for monthly water consumption rate from 2.5$ to 3.3$ with the same change rate [20].

Dubai-case a

In this case, the basic model is used with related prices and boundaries. In this model all three systems have unlimited cooling production capacity and by this, reMIND could choose which system is a better match for related condition.

Results Dubai-case a

The yearly system cost is 544.3$ and the table 6 shows other output data for 24 hours of a day.

Table 6: reMIND output data for Dubai-Case a

Hour	19	20	21	22	23	24	01	02	03	04	05	06
Cooling demand	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	0	0	0	0	0	0	0	0	0	0	0	9265
Cooling (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	0	0	100
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	100
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0

Table 6: (continued). reMIND output data for Dubai-Case a

Hour	07	08	09	10	11	12	13	14	15	16	17	18
Cooling demand	0	350	1400	2100	2730	2975	3675	3745	3850	2975	2100	1400
Cooling (chiller)	0	0	0	0	1123	0	3675	3745	3850	2975	2100	1400
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (PCWCC)	0	350	1400	2100	1607	2975	0	0	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	0	0	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0

Analysis Dubai-case a

According to table 6, the optimization is to determine the suppliers of the demands, cooling and water. In this table, the cooling demand is supplied by Evaporative chiller and PCWCC and water demand is supplied by PCWCC. The results shows that there is no surplus water and this means that in this case the water demand makes the PCWCC economical compare to evaporative chiller and when there is no need for water the cooling demand supply by evaporative chiller is cheaper and this is why the ITES is not working in any of time steps. It also should be noted that the PCWCC works two hour before starting the working day since the ice storage time, and as a result ice storage loss, is minimized and in selected time the environment temperature also is minimum.

Dubai-Case b

In this case, the ITES and PCWCC ice production rate is limited to 3500kW/h and reMIND should find the best match for related condition. It should be noted that the 3500kW/h comes from dividing the total cooling demand to electricity low price of Kerman study case.

Results Dubai-case b

The yearly system cost is 553.6$ and the hourly table 7shows other output data for 24 hours of a day.

Table 7: reMIND output data for Dubai-Case b

Hour	19	20	21	22	23	24	01	02	03	04	05	06
Cooling demand	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	0	0	0	0	0	0	0	0	0	0	3500	3500
Cooling (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	0	38	38
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	0	0	0	0	0	0	0	0	0	0	38	38
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0

Table 7 (continued): reMIND output data for Dubai-Case b

Hour	07	08	09	10	11	12	13	14	15	16	17	18
Cooling demand	0	350	1400	2100	2730	2975	3675	3745	3850	2975	2100	1400
Cooling (chiller)	0	0	0	0	1144	0	3675	3745	3850	2975	2100	1400
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	2265	0	0	0	0	0	0	0	0	0	0	0
Cooling (PCWCC)	0	350	1400	2100	1586	2975	0	0	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	24	0	0	0	0	0	0	0	0	0	0	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	24	0	0	0	0	0	0	0	0	0	0	0
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0

Analysis Dubai-case b

The optimization is to determine the suppliers of the demands, cooling and water. In table 7, the cooling demand again is supplied by evaporative chiller and PCWCC and water demand is supplied by PCWCC. However, the trend of PCWCC working time is limited to its capacity, 3500kW/h, and again there is no surplus water and this means that the water demand makes the PCWCC economical compare to evaporative chiller and when there is no need for water, the cooling demand supply by evaporative chiller is cheaper. Similarly, the ITES is not working in any time step. Also, the PCWCC works on hours near starting the working day since the ice storage time and as a result ice storage loss is minimized. It should be noted that the total cost of operation is slightly more than the case a since some part of produced ice should be store for longer time and this means more ice loss for thermal loss of system.

Dubai-case c

In cases "a" and "b", the PCWCC water outputs were unlimited but there were no revenue for surplus water. In case c, it is assumed that the surplus water is sold to government with the same price of water supply. This means that a local PCWCC can supply part of the region's local water demand or the water could be stored to be used when there is no need for cooling system but the water is required, like winter case.

Results Dubai-case c

The yearly system cost is -384.8$. This negative value shows that the revenue from sold water is more than the electricity cost for cooling demand. Table 8shows other output data for 24 hours of a day.

Table 8: reMIND output data for Dubai-Case c

Hour	19	20	21	22	23	24	01	02	03	04	05	06
Cooling demand	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	3500	3500	3500	3500	3500	3500	3500	3500	3500	3500	3500	3500
Cooling (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Cooling	3500	3500	3500	1008	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	38	0	38	24	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0

Table 8: (continued): reMIND output data for Dubai-Case c

Hour	19	20	21	22	23	24	01	02	03	04	05	06
Water (PCWCC)	38	38	38	38	38	38	38	38	38	38	38	38
Extra Water	38	38	38	38	38	38	38	0	38	0	13	38
Hour	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Cooling demand	0	350	1400	2100	2730	2975	3675	3745	3850	2975	2100	1400
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (PCWCC)	0	350	1400	2100	2730	2975	3675	3745	3850	2975	2100	1400
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	0	0	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	38	0	0	0	0	0	0	0	0	0	0	0
Extra Water	38	0	0	0	0	0	0	0	0	0	0	0

Analysis Dubai-case c

The optimization is to determine the suppliers of the demands, cooling and water. In table 8, both cooling demand and fresh water demand are supplied only by PCWCC and there is surplus water production as well. The trend of PCWCC working time shows that it is working with its full capacity, limited to 3500kW/h, and even though there is no demand for extra cooling from PCWCC, again the water demand makes the PCWCC economical compare to evaporative chiller and ITES. In this case the system cost is negative, -384.8$, and this value is the revenue from sold water. However, the real gain of the system compare to case b is this 384.8 plus the saved 553.6$ of case b. So, the real benefit of PCWCC compare to case b is 938.4$.

Texas

According to the figure 14 of thermal analysis chapter, in a typical summer day of Texas-USA the ambient temperature trend of Texas is similar to Dubai and the temperature does not vary considerably from day to night; however, the temperature levels are lower than Dubai and the maximum temperature difference for a 24 hours of a typical summer day is $7°C$. For other input data, the electricity price in this city follows the open market trend and it does not have a predefined value. Actually, the electricity price is defined by a balance between demand and supply, so, to consider an input value, it is assumed the electricity price for all 24 hours is constant with the average value of the electricity price in year 2015. For this study, the industrial building, the electricity price is 0.053$. The fresh water price is constant and equal to1.01$ [21].

Texas-case a

In this case the basic model is used with related prices and boundaries. In this model, all three systems have unlimited cooling production capacity and by this reMIND could choose which system is a better match for related condition.

Results Texas-case a

The yearly system cost is 254.3$ and the hourly table 9shows other output data for 24 hours of a day.

Table 9: reMIND output data for Texas-Case a

Hour	19	20	21	22	23	24	01	02	03	04	05	06
Cooling demand	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	0	0	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0
Hour	07	08	09	10	11	12	13	14	15	16	17	18
Cooling demand	0	350	1400	2100	2730	2975	3675	3745	3850	2975	2100	1400
Cooling (chiller)	0	350	1400	2100	1199	0	3675	0	3850	2975	2100	1400
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	9265	0	0	0	0	0	0	0	0	0	0	0
Cooling (PCWCC)	0	0	0	0	1531	2975	0	3745	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	100	0	0	0	0	0	0	0	0	0	0	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	100	0	0	0	0	0	0	0	0	0	0	0
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0

Analysis Texas-case a

The optimization is to determine the suppliers of the demands, cooling and water. In table 9, the cooling demand is supplied by evaporative chiller and PCWCC and water demand is supplied by PCWCC. The results shows that there is no surplus water and this means that in this case the water demand makes the PCWCC economical compare to evaporative chiller and when there is no need for water, the cooling demand supply by evaporative chiller is cheaper and this is why the ITES is not working in any of time steps. The difference of table 6 & 9 is in the working hour of PCWCC. Actually, in this table PCWCC works one hour later than Dubai case as the ambient temperature is lower in this time. Total price of system is less than Dubai since the power price and temperature levels are lower.

Texas-Case b

In this case, the ITES and PCWCC ice production rate is limited to 3500kW/h and reMIND should find the best match for related condition. It should be noted that the 3500kW/h comes from dividing the total cooling demand to electricity low price of Kerman study case.

Results Texas-case b

The yearly system cost is 255.3$ and the hourly table 10shows other output data for 24 hours of a day.

Table 10: reMIND output data for Texas-Case b

Hour	19	20	21	22	23	24	01	02	03	04	05	06
Cooling demand	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	0	0	0	0	0	0	0	0	0	0	2265	3500
Cooling (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	0	24	38
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	0	0	0	0	0	0	0	0	0	0	24	38
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0
Hour	07	08	09	10	11	12	13	14	15	16	17	18
Cooling demand	0	350	1400	2100	2730	2975	3675	3745	3850	2975	2100	1400
Cooling (chiller)	0	350	1400	2100	1346	0	3675	0	3850	2975	2100	1400
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	3500	0	0	0	0	0	0	0	0	0	0	0
Cooling (PCWCC)	0	0	0	0	1384	2975	0	3745	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	38	0	0	0	0	0	0	0	0	0	0	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	38	0	0	0	0	0	0	0	0	0	0	0
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0

Analysis Texas-case b

The optimization is to determine the suppliers of the demands, cooling and water. In table 10, the cooling demand again is supplied by evaporative chiller and PCWCC and water demand is supplied by PCWCC. However, the trend of PCWCC working time is limited to its capacity, 3500kW/h, and again there is no surplus water and this means that the water demand makes the PCWCC economical compare to evaporative chiller and when there is no need for water, the cooling demand supply by evaporative chiller is cheaper. Similarly, the ITES is not working in any of time steps. Also, the PCWCC works on hours near starting the working day since the ice storage time and as a result ice storage loss is minimized. Here, the total cost of operation also is slightly more than the case a since some part of produced ice should be store for longer time and this means more ice loss for thermal loss of system. Again, the total price of the system is less than Dubai since the power price and temperature levels are lower.

Texas-case c

In cases "a" and "b", the PCWCC water outputs were unlimited but there were no revenue for surplus water. In case "c", it is assumed that the surplus water is sold to government with the same price of water supply. This means that, a local PCWCC can supply part of the region's local water demand or the water could be stored to be used when there is no need for cooling system but the water is required, like winter case.

Results Texas-case c

The yearly system cost is 73$ and the hourly table 11shows other output data for 24 hours of a day.

Table 11: reMIND output data for Texas-Case c

Hour	19	20	21	22	23	24	01	02	03	04	05	06
Cooling demand	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	0	0	0	2492	3500	3500	3500	3500	3500	3500	3500	3500
Cooling (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Cooling	0	0	0	238	3500	3500	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	38	38	0	24	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	0	0	0	27	38	38	38	38	38	38	38	38
Extra Water	0	0	0	27	38	38	38	0	0	38	13	38
Hour	07	08	09	10	11	12	13	14	15	16	17	18
Cooling demand	0	350	1400	2100	2730	2975	3675	3745	3850	2975	2100	1400
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	3500	0	0	0	0	0	0	0	0	0	0	0
Cooling (PCWCC)	0	350	1400	2100	2730	2975	3675	3745	3850	2975	2100	1400
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	0	0	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	38	0	0	0	0	0	0	0	0	0	0	0
Extra Water	38	0	0	0	0	0	0	0	0	0	0	0

Analysis Texas-case c

The optimization is to determine the suppliers of the demands, cooling and water. In table 11, the cooling demand is supplied only by PCWCC and water demand is supplied by PCWCC and there is surplus water production as well. The trend of PCWCC working time shows that PCWCC is working with its full capacity, limited to 3500kW/h, only when the cooling demand is supplied by PCWCC and there is no extra cooling. Here, the combination of the cooling demand and water demand makes the PCWCC economical compare to evaporative chiller and ITES. In this case the system cost is negative, 73$, and compare to case b, this case saves 152.3$ by selling the produced water. This saving is much lower than the Dubai case, 938.4$, mainly because of the water price. In Dubai case, the water price is almost 3.3 times more than Texas case.

Kerman

According to the figure 12 of thermal analysis chapter, in a typical summer day of Kerman, the ambient temperature in Kerman-Iran, is very hot in days but the night is relatively cool and the maximum temperature difference for a 24 hours of a typical summer day is$19°C$. The electricity price in Iran is different during day and night and it is as follows:

07:00~19:00 = 1560 Rials= 0.045$

19:00~23:00 = 3120 Rials= 0.08$

23:00~07:00 = 780 Rials = 0.023$ [22]

(With the change rate of 1$=347300Rials)

The fresh water in Iran is subsidized and it is only 0.32$ for each cubic meter of water. Also, there are an extra charge for waste water disposal, this fee is charged according to consumed fresh water and it is 0.116$ per cubic meter of fresh water consumption. So, the real price of water in Iran is 0.432$ per cubic meter of consumed fresh water [23]. However, Iran government established some projects to use desalinated water and to sell water by private sector. By this plan, the real value of produce fresh water from sea water plus its waste disposal is 1.56$ [24].

Kerman-case a-1

In this case, the basic model is used with related prices and boundaries of subsidized water price. In this model all three systems have unlimited cooling production capacity and by this reMIND could choose which system is a better match for related condition. The water price in this case is 0.432$, the subsidized price of the fresh water.

Results Kerman-case a-1

The yearly system cost is 117.6$ and the hourly table 12shows other output data for 24 hours of a day.

Table 12: reMIND output data for Kerman-Case a-1, power peak hours and off-peak hours cells are highlighted

Hour	19	20	21	22	23	24	01	02	03	04	05	06
Cooling demand	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	0	0	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0
Hour	07	08	09	10	11	12	13	14	15	16	17	18
Cooling demand	0	0	350	1400	2100	2730	2975	3675	3745	3850	2975	2100
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	18845	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	1100	3675	3745	3850	2975	2100
Ice from PCWCC	9265	0	0	0	0	0	0	0	0	0	0	0
Cooling (PCWCC)	0	0	350	1400	2100	2730	1875	0	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	100	0	0	0	0	0	0	0	0	0	0	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	100	0	0	0	0	0	0	0	0	0	0	0
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0

Analysis Kerman-case a-1

The optimization is to determine the suppliers of the demands, cooling and water. In table 11, the cooling demand is supplied by ITES and PCWCC and water demand is supplied by PCWCC and unlike Dubai and Texas cases, in this case the evaporative chiller is not in service. The results shows that there is no surplus water and this means that in this case the water demand makes the PCWCC economical compare to ITES and when there is no need for water, the cooling demand supply by ITES is cheaper due to its less ice waste during water treatment time. The differences of table 6, 9& 12 is in the working hours of the ITES and evaporative chiller, actually in this table the ITES is chosen by reMIND optimization software since the power price is less during night hours. Total price of system is less than Dubai & Texas because the power price is lower.

Kerman-case a-2

In this case, the basic model is used with related prices and boundaries and all three systems have unlimited cooling production capacity and by this, reMIND could choose which system is a better match for related condition. The water price in this case is 1.56$, the real price of the fresh water without subsides.

Results Kerman-case a-2

The yearly system cost is 117.6$ and the hourly table 12shows other output data for 24 hours of a day.

Table 13: reMIND output data for Kerman-Case a-2, power peak hours and off-peak hour cells are highlighted

Hour	19	20	21	22	23	24	01	02	03	04	05	06
Cooling demand	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	0	0	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0
Hour	07	08	09	10	11	12	13	14	15	16	17	18
Cooling demand	0	0	350	1400	2100	2730	2975	3675	3745	3850	2975	2100
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	18845	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	1100	3675	3745	3850	2975	2100
Ice from PCWCC	9265	0	0	0	0	0	0	0	0	0	0	0
Cooling (PCWCC)	0	0	350	1400	2100	2730	1875	0	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	100	0	0	0	0	0	0	0	0	0	0	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	100	0	0	0	0	0	0	0	0	0	0	0
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0

Analysis Kerman-case a-2

The results of table 12 are exactly similar to table 11. However, it should be noted that, the saved water price in this case is much higher than case a-1. Actually, in this case the PCWCC saves 1560$ for producing fresh water and it is only 432$.

Kerman-Case b-1

In this case, the ITES and PCWCC ice production rate is limited to 3500kW/h and reMIND should find the best match for related condition. It should be noted that the 3500kW/h comes from dividing the total cooling demand to electricity low price of

Kerman study case. In this case the water price is according to subsidized tariff of water, 0.432$ per cubic meter of fresh water.

Results Kerman-case b-1

The yearly system cost is 127.7$ and the hourly table 13shows other output data for 24 hours of a day.

Table 14: reMIND output data for Kerman-Case b-1, power peak hours and off- peak hours cells are highlighted.

Hour	19	20	21	22	23	24	01	02	03	04	05	06
Cooling demand	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	245	3500	3500	3500	3500	3500
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	0	0	0	0	0	0	0	0	0	2265	3500	3500
Cooling (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	24	38	38
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	0	0	0	0	0	0	0	0	0	24	38	38
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0
Hour	07	08	09	10	11	12	13	14	15	16	17	18
Cooling demand	0	350	1400	2100	2730	2975	3675	3745	3850	2975	2100	1400
Cooling (chiller)	0	350	976	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	3675	3745	3850	2975	2100	1400
Ice from PCWCC	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (PCWCC)	0	0	424	2100	2730	2975	0	0	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	0	0	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0

Analysis Kerman-case b-1

The optimization is to determine the suppliers of the demands, cooling and water. In table 14, the cooling demand again is supplied by ITES and PCWCC and water demand is supplied by PCWCC. However, the trend of ITES and PCWCC working time is limited to their capacity, 3500kW/h, and again there is no surplus water and this means that in this case the water demand makes the PCWCC economical compare to ITES and when there is no need for water, the cooling demand supply by ITES is cheaper due to its less ice waste during water treatment time. Similarly, the ice evaporative chiller is not working in any of time steps. Both ITES and PCWCC work on hours near starting of the working day since the ice storage time and as a result ice storage loss is minimized. Here also, the total cost of operation is slightly more than the case a-1 since some part of produced ice should be store for longer time and this means more ice loss for thermal loss of system. Again, the total price of the system is less than Dubai and Texas since the power price level is lower.

Kerman-caseb-2

In this case, the ITES and PCWCC ice production rate is limited to 3500kW/h and reMIND should find the best match for related condition. It should be noted that the 3500kW/h comes from dividing the total cooling demand to electricity low price of Kerman study case. The water price in this case is 1.56$, the real price of the fresh water without subsides.

Results Kerman-case b-2

The yearly system cost is 127.7$ and the hourly table 15shows other output data for 24 hours of a day.

Table 15: reMIND output data for Kerman-Case b-2, power peak hours and off-peak hours cells are highlighted

Hour	19	20	21	22	23	24	01	02	03	04	05	06
Cooling demand	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	245	3500	3500	3500	3500	3500
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	0	0	0	0	0	0	0	0	0	2265	3500	3500
Cooling (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	24	38	38
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	0	0	0	0	0	0	0	0	0	24	38	38
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0
Hour	07	08	09	10	11	12	13	14	15	16	17	18
Cooling demand	0	350	1400	2100	2730	2975	3675	3745	3850	2975	2100	1400
Cooling (chiller)	0	350	976	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	3675	3745	3850	2975	2100	1400
Ice from PCWCC	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (PCWCC)	0	0	424	2100	2730	2975	0	0	0	0	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	0	0	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Water	0	0	0	0	0	0	0	0	0	0	0	0

Analysis Kerman-case b-2

The results of table 15 are exactly similar to table 14. In this table also, the saved water price is much higher than case b-1. Actually, in this case the PCWCC saves 1560$ for producing fresh water and it is only 432$.

Kerman-case c-1

In cases "a" and "b", the PCWCC water outputs were unlimited but there were no revenue for surplus water. In case c, it is assumed that the surplus water is sold to government with the same price of water supply. This means that a local PCWCC can supply part of the region's local water demand or the water could be stored to be used when there is no need for cooling system but the water is required, like winter case. In this case the water price is according to subsidized tariff of water, 0.432$ per cubic meter of fresh water.

Results Kerman-case c-1

The yearly system cost is 24.1$ and the hourly table 16shows other output data for 24 hours of a day.

Table 16: reMIND output data for Kerman-Case c-1, power peak hours and off-peak hours cells are highlighted

Hour	19	20	21	22	23	24	01	02	03	04	05	06
Cooling demand	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	3500
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	0	0	0	0	3500	3500	3500	3500	3500	3500	3500	3500
Cooling (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Cooling	0	0	0	0	2029	3500	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	0	0	100
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	0	0	0	0	38	38	38	38	38	38	38	38
Extra Water	0	0	0	0	38	13	0	0	38	38	38	38
Hour	07	08	09	10	11	12	13	14	15	16	17	18
Cooling demand	0	350	1400	2100	2730	2975	3675	3745	3850	2975	2100	1400
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	2100	1400
Ice from PCWCC	1259	0	0	0	0	0	0	0	0	0	0	0
Cooling (PCWCC)	0	350	1400	2100	2730	2975	3675	3745	3850	2975	0	0
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	0	0	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	14	0	0	0	0	0	0	0	0	0	0	0
Extra Water	14	0	0	0	0	0	0	0	0	0	0	0

Analysis Kerman-case c-1

The optimization is to determine the suppliers of the demands, cooling and water. In table 16, the cooling demand is supplied only by PCWCC and water demand is supplied by PCWCC and there is surplus water production as well. The trend of PCWCC working time shows that it is working with its full capacity, limited to 3500kW/h, only when the electricity price is low and as a result there is some extra cooling from PCWCC which is wasted. Here, the water demand itself makes the PCWCC economical compare to evaporative chiller and ITES. In this case, the system cost is only 24$ and compare to case b, this case saves 103$ by selling the produced water. This saving is lower than the Dubai and Texas cases, 938.4$ & 152.3 respectively, because the daily cost of system in case b-1 was lower due to cheap electricity and fresh water in Iran.

Kerman-case c-2

This case is similar to case 1, except the water price in this case is 1.56$, the real price of the fresh water without subsides.

Results Kerman-case c-2

The yearly system cost is -359.5$ and the hourly table 17shows other output data for 24 hours of a day.

Table 17: reMIND output data for Kerman-Case c-2, power peak hours and off-peak hours cells are highlighted

Hour	19	20	21	22	23	24	01	02	03	04	05	06
Cooling demand	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	0	0	0	2492	3500	3500	3500	3500	3500	3500	3500	3500
Cooling (PCWCC)	0	0	0	0	0	0	0	0	0	0	0	0
Extra Cooling	0	0	0	238	3500	3500	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	0	0	100
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	0	0	0	27	38	38	38	38	38	38	38	38
Extra Water	0	0	0	27	38	13	0	0	38	38	38	38
Hour	07	08	09	10	11	12	13	14	15	16	17	18
Cooling demand	0	350	1400	2100	2730	2975	3675	3745	3850	2975	2100	1400
Cooling (chiller)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from TES	0	0	0	0	0	0	0	0	0	0	0	0
Cooling (ITES)	0	0	0	0	0	0	0	0	0	0	0	0
Ice from PCWCC	3500	0	0	0	0	0	0	0	0	0	0	0
Cooling (PCWCC)	0	350	1400	2100	2730	2975	3675	3745	3850	2975	2100	1400
Extra Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Water demand	0	0	0	0	0	0	0	0	0	0	0	0
Purchased water	0	0	0	0	0	0	0	0	0	0	0	0
Water (PCWCC)	38	0	0	0	0	0	0	0	0	0	0	0
Extra Water	38	0	0	0	0	0	0	0	0	0	0	0

Analysis Kerman-case c-2

The optimization is to determine the suppliers of the demands, cooling and water. In table 17, the cooling demand is supplied only by PCWCC and water demand is supplied by PCWCC and there is surplus water production as well. The trend of PCWCC working time shows that it is working with its full capacity, limited to 3500kW/h, only when the electricity price is low and with partial capacity at 22:00 o'clock when the electricity price is in its peaks. As a result, there is some extra cooling from PCWCC which is wasted. Here, the water demand itself makes the PCWCC economical compare to evaporative chiller and ITES even in electricity peak prices. In this case, the system cost is negative, -359.5$, and compare to case b-2, this case saves 483$ by selling the extra produced water. This saving is lower than the Dubai case, 938.4$, because the daily cost of system in case b-1 was lower due to cheap electricity and fresh water in Iran. It should be noted that in this case compare to c-1 the PCWCC produces more extra cooling and heat and works in electricity peak hours.

Result and Analysis (Part B)

In the scenarios of part A, all three cooling systems, single evaporative compressor Chiller, ITES, and PCWCC, are in service and reMIND chooses the best combination for their working plan. Although, these scenarios are good for comparing between all three options in different boundary conditions, the results are not realistic as in reality only one system is used by building owners. In this part, each system is simulated separately for all three cities and the results, electricity consumption and total cost, are given in graphs. It should be mentioned that the total cost is electricity price plus water price.

In below graphs, the PCWCC (case c) refers to case c of part A in which the surplus water could be sold and Kerman-1 and Kerman-2 refer to subsidized price and real price of water in Kerman which are 0.432$ and 1.56$ respectively.

Evaporative compressor chiller power consumption

In this case, the evaporative compressor chillers in all three cities are working as the only suppliers of cooling demand. Figure 21 shows the electricity consumptions of each case. In this scenario the cooling demand is same for all three cases and the electricity consumption difference is from the temperature level difference in each city. According to this graph, Dubai uses more electricity than Texas or Kerman.

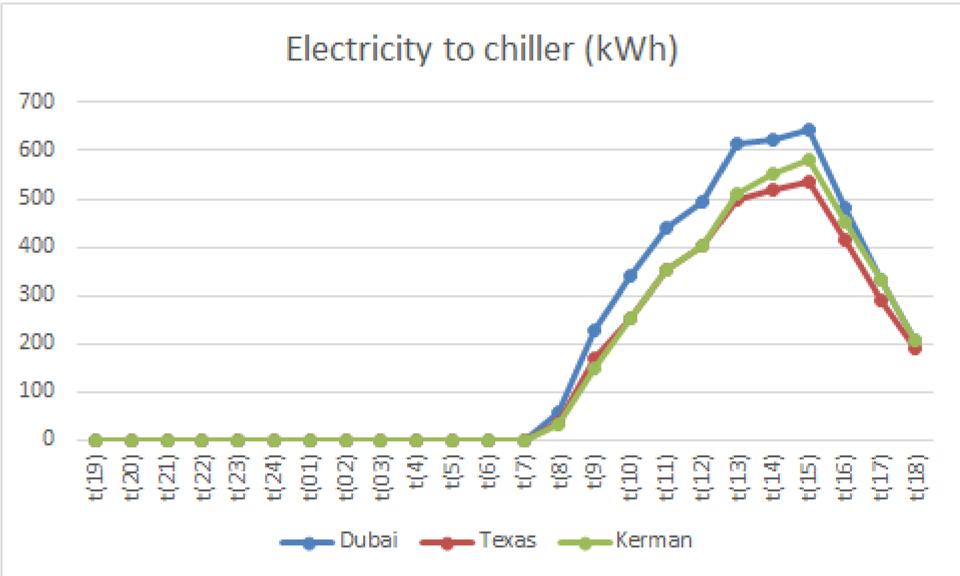


Figure 21: The graph of electricity consumption of evaporative chiller in each city

ITES power consumption

This scenario corresponds to the ITES system with 3500kWh ice production capacity and full ice storage design in each city and figure 22 shows the electricity consumption for each city. According to this figure, the electricity consumption in Dubai is more than two other cities, Texas and Kerman. It also should be noted that the electricity consumption in Dubai and Texas is only depended on ambient temperature but in Kerman it is depended on ambient temperature as well as the power price. As a result, the electricity consumption in Kerman is in off-peak hours but in Dubai and Texas it is near working hours to reduce the wasted ice in storage time.

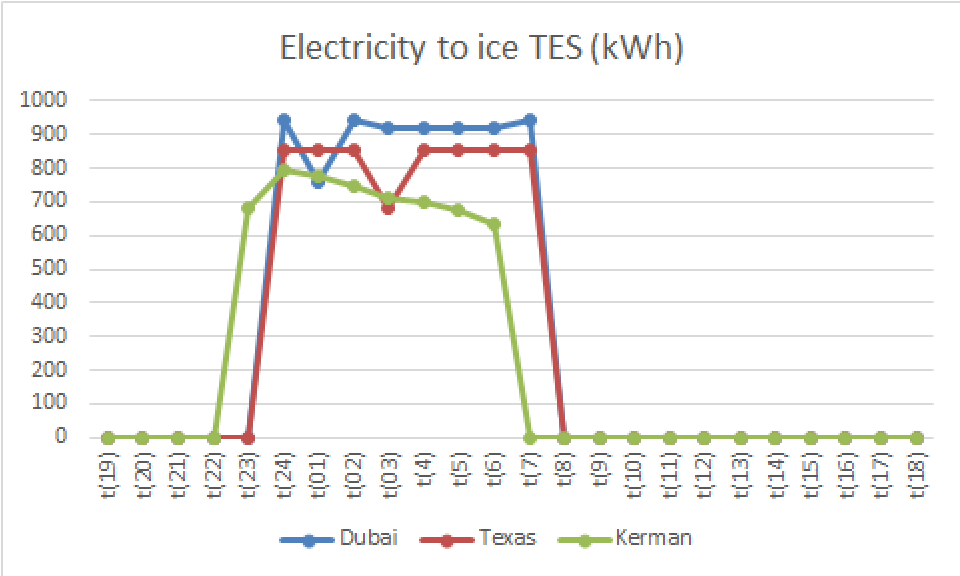


Figure 22: The graph of electricity consumption of ITES in each city

PCWCC power consumption

This scenario corresponds to the PCWCC system with 3500kWh ice production capacity and full ice storage design in each city and figure 23 shows the electricity consumption for each city. In this scenario, the extra water is not sold and as a result there is no revenue from extra water production. According to figure 23, the electricity consumption in Dubai is more than two other cities, Texas and Kerman, because of its higher temperature level. All three cases produce no extra cooling; however, there is surplus water which is not sold to government.

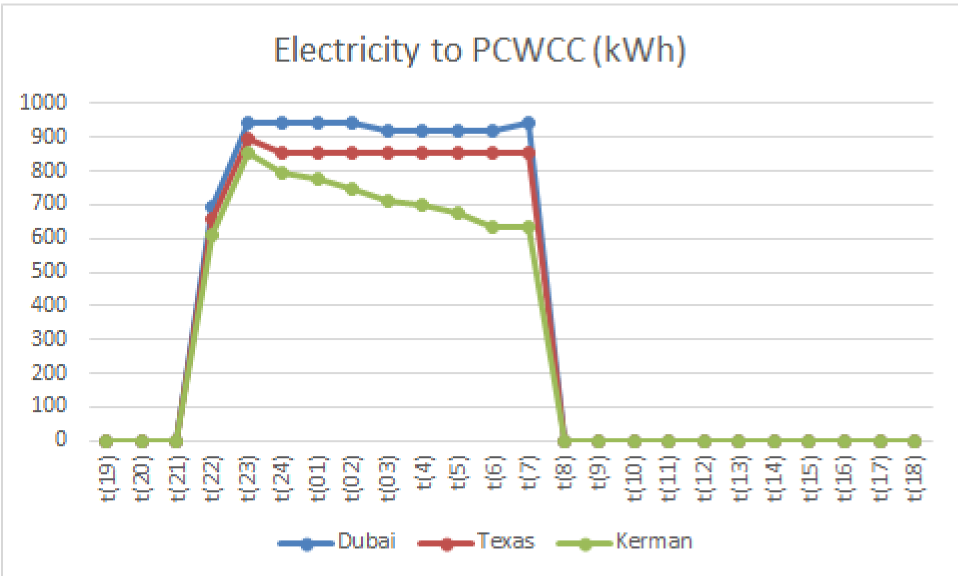


Figure 23: The graph of electricity consumption of PCWCC in each city without revenue from extra water production

PCWCC (case c) power consumption

This scenario corresponds to the PCWCC system with 3500kWh ice production capacity and full ice storage design in each city. In this scenario, the extra water is sold to government and as a result there is some revenue from extra water production. Figure 24 shows the electricity consumption for each city. According to this figure, the electricity consumption in all three cities are more than figure 23 and this means that the

PCWCC works in more hours of a day to produce more fresh water. Considering that in figure 23, whole electricity were used to satisfy the cooling demand, in this scenario the electricity consumption is more and this means that surplus cooling is produced in these three cities. It should be noted that the electricity consumption profile in Dubai and Texas are dependent on ambient temperature and in Kerman is dependent on both ambient temperature and electricity price. The graph of Dubai shows that for its higher fresh water revenue per cubic meter of water, the PCWCC works with its full capacity even when the ambient temperature is high.

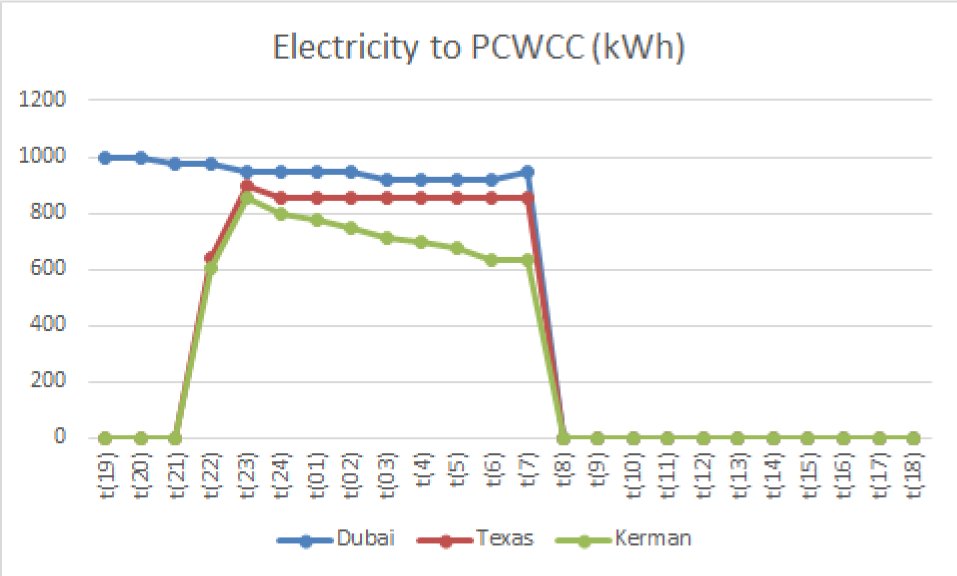


Figure 24: The graph of electricity consumption of PCWCC in each city with revenue from extra water production

Above mentioned graphs are for electricity consumption of each city and because of different prices and ambient temperatures, it is not clear that in which city the cost of (or revenue from) systems are higher or lower and the pay-back time could not be calculated without such data. So, following bar-charts are for total daily cost and revenue from systems and give a more precise view for investment potentials of each system.

Total (electricity and fresh water) daily cost

In below mentioned figure 25, the total daily cost of each system in each city is given in dollars. The shown costs in this figure are for both electricity and fresh water cost and the revenue of sols fresh water, PCWCC case c. From this bar chart, it is clear that the cost of all four systems, chiller, ITES, and both PCWCCs, are high in Dubai case for its higher electricity. The interesting point is that, when there is no revenue from fresh water, except for Kerman, in both Dubai and Texas the daily cost of evaporative chiller is lower than two other systems since the electricity price is constant in these two cities. However, in Kerman, the evaporative chiller, ITES, and PCWCC without revenue from fresh water are almost in a same level. In final case, PCWCC (case c), the PCWCC is more economical for all three cities and even in Dubai and Kerman (case c), the sold fresh water revenue is more than spent money for bought electricity.

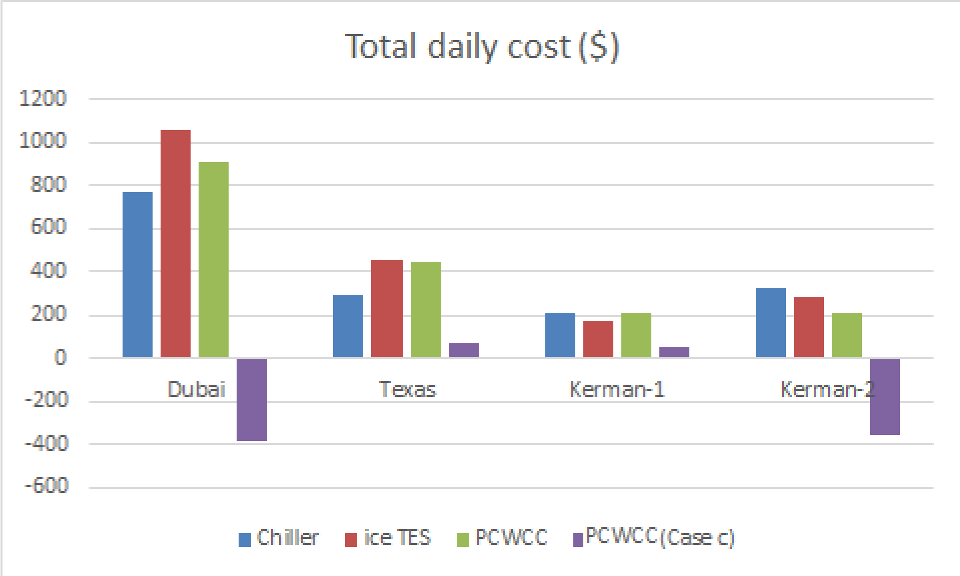


Figure 25: The bar chart of daily electricity and fresh water cost

Total daily revenue from PCWCC

In figure 26, the revenue from PCWCC per kWh of consumed electricity is shown for two assumptions: no selling extra fresh water and selling extra fresh water. The negative values show that there is no revenue from PCWCC and actually the revenue from fresh water is less than consumed electricity prices. The positive values show how much the PCWCC is economical. According to this figure, investment on PCWCC in Dubai is very interesting if there will be a chance to sell fresh water since the fresh water is very expensive in Dubai. Kerman is the next interesting place when the fresh water prices are not subsidized.

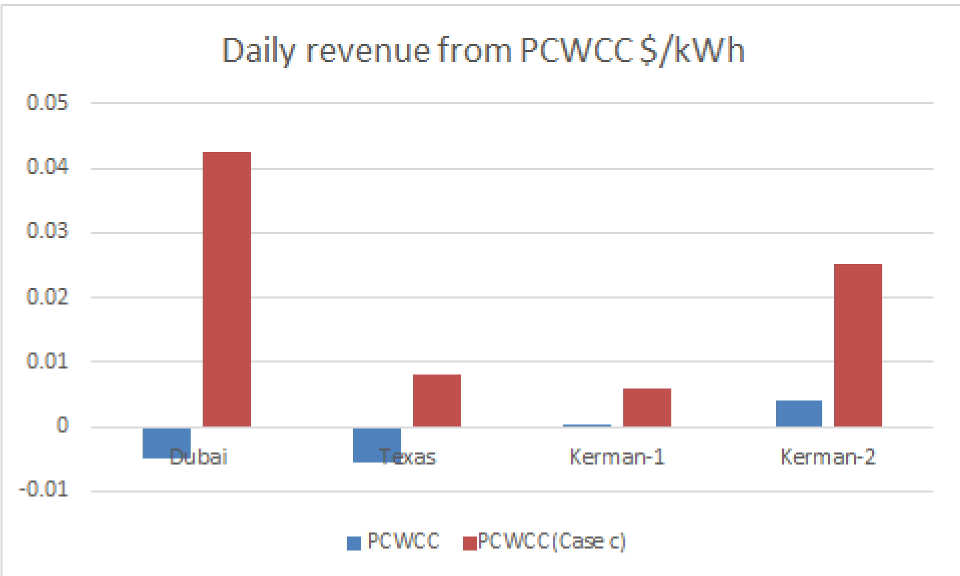


Figure 26: The bar chart of revenue from PCWCC per kWh of consumed electricity in a typical summer day

DISCUSSION

Analyzing different scenarios of three cities shows that the PCWCC is economical in cases with cheaper off-peak hour electricity price or in cases where the fresh water price is high. This means that in cities with constant electricity price and low fresh water price the PCWCC could not compete with evaporative cooler or other commercial AC systems since the revenue from fresh water production could not cover the reduced cooling efficiency of the PCWCC. In cities with variable electricity price, like Kerman in this study, the PCWCC and ITES both are economical; however, the water treatment ability of PCWCC makes it a better choice and the produced fresh water covers the efficiency loss of PCWCC compare to ITES and this lower cost of total electricity and fresh water may be enough for installation cost of PCWC.

Fresh water price itself is a very important factor and as a result in countries with hot weather condition and no subsidies on fresh water, the PCWCC is a suitable choice for major fresh water users' investment. This also is true when the surplus fresh water could be sold to government or other users. This revenue from surplus fresh water is a realistic option since the treated water has a very high purity level and could be pumped to city water network without major change in the existing network system.

Although, technically the revenue from fresh water seems practical, a new challenge is discovered in this study. At the introductions of this thesis it is assumed that the fresh water production is a close cycle and PCWCC will produce all required fresh water from waste water of the building. This could not be done since only 15% of the waste water is treated to fresh water and the concentration of remaining 85% is very high for PCWCC operation and must be wasted. This means that there is always need for another source of waste/raw water. This source should be studied case by case. As an example, in the Dubai case study of this thesis with revenue from fresh water, the total produced fresh water is 494 cubic meters. This is equal to 3293 cubic meters of inlet waste/raw water. This is more than building's waste water because the waste water itself is produced from used fresh water, 100 cubic meter in our study. Hence, another source of raw water is required and in Dubai case this could be sea water. In Kerman city this could be salty water from underground sources because the salty water level usually is high in hot and dry cities.

Another point of the study is the cooling load. In this study, the cooling load profile is assumed as a typical load of an industrial building, so, for more specific results this should be replaced by exact simulation of building's cooling demand at the given ambient condition. This could be another project to model the building and to find out its cooling demand variation with ambient temperature and humidity variation. Also, for more precise results, the thermodynamic values of β, coefficient of performance, should be replaced by real values of common cooling/refrigeration systems. However, these two items does not seem to change the overall results as they both effect evaporative chiller and PCWCC or ITES in same ratios and may higher or lower all results in a same range.

CONCLUSIONS

First chapter of this study shows the possibility of combining an ITES with desalination by freezing system and to have a Power storage, Cooling storage, and Water production Combined Cycle, PCWCC. To do this, the "ice slurries" ITES is a perfect match for desalination by freezing cycle and could be used in PCWCC. Also, from known ice separation options in desalination by freezing systems, the gravity ice separations seems more suitable for PCWCC for its both suitable working periods and less energy wastes. These show that the PCWCC is a practical idea and its parts are already studied in many papers.

Second and third chapters, discuss the thermodynamic equations of all three systems, evaporative chillers, ITES, and PCWCC and the results are input data of the cost modeling by reMIND, chapter four. This chapters' final results are thermodynamic efficiencies of all above mentioned systems as well as the fresh water production rate of PCWCC per kWh of required cooling and these are input data for reMIND modeling software and they are used in finding the internal equations and boundaries of the models.

Finally, the reMIND models are built for three cities, Kerman, Dubai, and Texas, with similar ambient temperature trends and with different electricity and fresh water tariffs. The reMIND outputs show that the PCWCC is economical only where there is a significant electricity price difference between ice charging and ice melting hours, off-peak and on-peak hours, or where the fresh water price is high compare to electricity price. The results show that unsubsidized fresh water price in cities like Kerman, scenario case 2, and Dubai when the fresh water is provided by desalination systems makes the PCWCC economical even when there is no need for cooling. Even in cities with low fresh water tariff, the revenue from selling the surplus fresh water can cover part of total electricity cost of system and shifts the power consumption from on-peak hours to off-peak hours.

This thesis shows the idea of PCWCC and its benefits in many aspects of modern life; however, this is the beginning step and the way to a commercial PCWCC is far. As it is mentioned in the thesis, the prototypes of desalination by freezing are made years ago and none of them left the laboratories for their efficiency issues and technical problems. The PCWCC suggests an incredible efficiency increase and by new technologies it may be possible to solve the technical problems and this could be the first step in practical work on PCWCC. Besides, next steps could be more detailed thermodynamic and process design of PCWCC and specially the ice separation part of it.

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