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Solar Heating in Commercial Buildings

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Abstract

Heating, ventilation, and air conditioning (HVAC) equipment accounts for 40% to 50% of a commercial building's energy usage. This energy is supplied using either electricity or natural gas. Combustion products from natural gas pollute the environment and the burning of fossil fuels to produce electricity also pollutes the environment. The world must turn to clean, renewable energy resources to stop pollution. Solar energy has the potential to play a huge role in the renewable energy movement. Solar energy can be harnessed through active or passive solar techniques. Active solar uses solar collectors to harness the sun's energy and passive solar uses heat transfer through architectural features to transfer the sun's energy as heat.

The exterior walls of commercial buildings are typically bare, plain walls. Why not use this space to harness solar energy for space heating? This report will analyze two identical commercial buildings, one in St. Louis, MO and one in Phoenix, AZ. Both buildings will have flat plate solar collectors installed on the south facing wall and the peaking heating demand will be compared to the amount of solar energy that can be harnessed at that time. The peak heating demands are calculated using Trace 700. It was found that on January 17th at 1:00 pm, the St. Louis system could harness 104.2kW of solar energy (33.2% of the heating demand) and the Phoenix system could harness 465.8 kW of energy (290.8% of the heating demand.) This proves that solar energy has the potential to play a huge role in the world of renewable energy, but the size of its impact is dependent upon location.

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Introduction

In a commercial building, heating, ventilation, and air conditioning (HVAC) equipment typically accounts for around 40% to 50% of the building's energy consumption, depending on the climate and other factors [1]. This energy is produced through the burning of natural gas, which produces combustion products that pollute our environment, or electricity, which is produced through the burning of fossil fuels that also pollute our environment. Solar energy is a vast and clean renewable energy resource that enhances sustainability and provides an alternative energy source to natural gas and the burning of fossil fuels to produce electricity. There are two types of technologies used to harness solar energy: active solar energy and passive solar energy. Active solar energy technologies use concentrated solar, solar water heating, and photovoltaic systems to harness the sun's energy. Passive solar energy uses the architectural features of a building such as windows, walls, and floors to collect, store, and distribute energy in the form of heat in the winter and reject solar heat in the summer [2]. This report will focus on the use of solar space heating in commercial buildings. Solar space heating can be accomplished using active solar or passive solar and is an excellent way to reduce energy consumption in commercial buildings.

A History of Solar Energy

The history of harnessing solar energy dates all the way back to 7th century B.C. with the use of a magnifying glass to concentrate the sun's energy to burn ants. It is also said that in 3rd century B.C. Greeks and Romans used mirrors to light torches for religious purposes. The concentration of solar energy using mirrors, magnifying glasses, and other reflective materials continued for many centuries [3]. It was not until 1876 that

William Grylls Adams and his student, Richard Day, discovered that when selenium is exposed to sunlight it produces electricity. Although the selenium cells were not efficient, they proved that light could be converted into electricity without moving parts or adding heat [4]. This discovery sparked the research and development of solar technologies in the scientific community. Advancements in solar energy technology continued throughout the 1900's until the technology that is seen today emerged. In 2015, the United States had over 23 gigawatts of photovoltaic capacity installed throughout the country. That is enough clean, renewable energy to provide enough electricity to power nearly 5 million homes [5]. Advancements in solar energy will continue to improve the efficiency and lower the cost of solar technology. Even though solar energy seems like the answer to our world's energy needs, it is limited by location.

How Solar Energy Varies With Location

It is estimated that the edge of the Earth's atmosphere sees 174,000 terawatts of incoming solar radiation, or insolation, each day. Around 30% of this insolation is reflected back into space while the rest is absorbed by the Earth. This is enough energy to sustain the world's energy needs many times over. However, not all of this energy can be harnessed. The majority of it is absorbed by the oceans and clouds. The amount of energy that can be harnessed is a function of distance from the equator. Because of the tilt of the Earth's axis, the equator is the place on Earth nearest to the sun, which means it sees the most insolation. For example, Phoenix, Arizona sees much more insolation than Seattle, Washington. The amount of solar insolation is equal to the irradiance above the atmosphere minus the atmospheric losses due to absorption and scattering. Thus irradiation is the total amount of power per unit area received from the sun [5]. A map of the global horizontal irradiation in North America can be seen below in Figure 1.

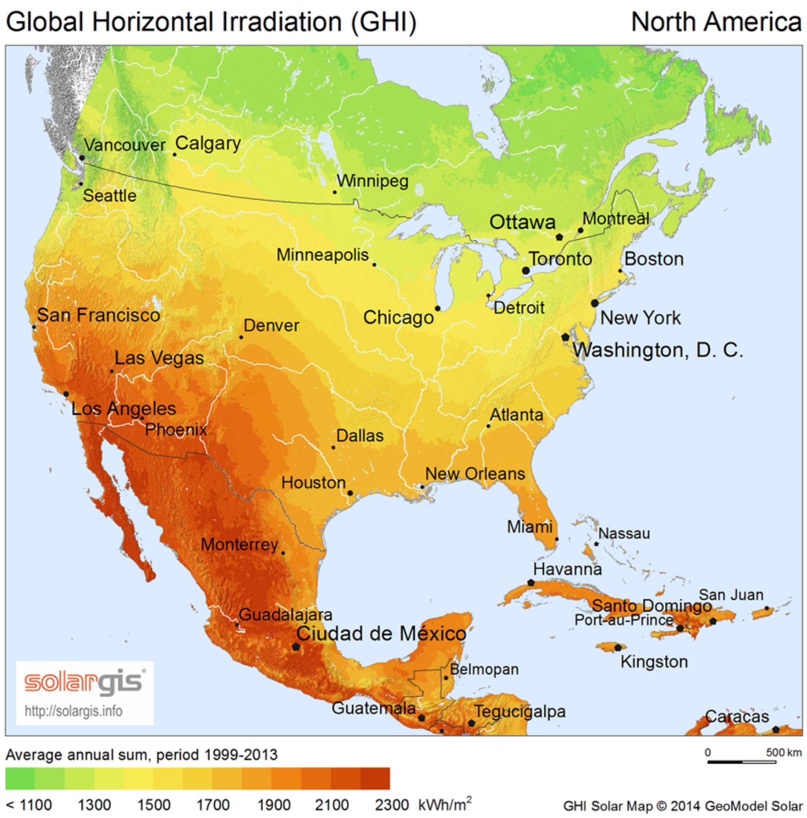


Figure 1. Map of global horizontal irradiation in North America.
http://solargis.com/products/maps-and-gis-data/free/download/north-america

Solar Energy and HVAC

Solar space heating can be a reliable and clean alternative energy resource for large commercial buildings with high heating demands. As noted previously, HVAC equipment accounts for about 50% of a building’s energy consumption [1]. The solar energy from the sun is a free, clean energy resource that can help reduce that percentage. As long as the sun shines, solar energy can be harnessed. Solar energy can be harnessed for solar space heating using active, passive, or both solar technologies [2]. Both methods of solar space heating will be discussed in this report along with which areas in the United States can gain the most from this technology.

Solar Space Heating: St. Louis, MO vs. Phoenix, AZ

This report will then compare the amount of solar energy that can be harnessed by identical commercial buildings in St. Louis, MO and Phoenix, AZ on a peak day in the middle of winter. An identical building will be placed in each city and the peak heating demand for each location will be calculated using TRACE 700. This peak heating demand will then be compared to the amount of solar energy that can be harnessed on January 17th at 1:00pm at the peak design temperatures. The peak design temperatures used are based on the ASHRAE design temperatures for each city. This comparison will provide a good understanding of the difference in the amount of insolation that each city receives due to distance from the equator (latitude). It will also allow for an educated guess at which location a solar heating system would be most cost effective in.

Solar Space Heating in Commercial Buildings

Heating in Commercial Buildings

Large commercial buildings are heated using many different methods in today's society. One advantage of commercial buildings is that they typically only need heat at the building's perimeter. This is because computers and other miscellaneous equipment that give off heat supply enough heat to satisfy interior spaces. Interior spaces also see none of the cold infiltration that leaks through the cracks of windows and doors. Perimeter heating is accomplished using multiple methods. One method is the use of baseboard heating. Baseboard heating is accomplished using either electric radiators or using a boiler to send hot water through fin tubes to transfer heat into the rooms. The second method is to heat the air being dumped into the room via the HVAC system. This air can be heated directly at the unit using natural gas or electric or it can be heated in a fan terminal unit just before being dumped into the room using electric or hot water. Both of these methods require an abundance of energy. The goal of solar space heating is to reduce or eliminate the need for these two heating methods.

Passive Solar Space Heating

Passive solar space heating takes advantage of the sun's energy through architectural design features such as large south-facing windows or materials that absorb heat during the day and then release it at night when it is needed. Passive solar space heating systems are typically designed using direct gain, indirect gain, or isolated gain. Direct gain uses the sun's direct solar energy to store heat in materials such as tile or concrete and then slowly releases the heat energy into the building. Indirect gain typically uses the building walls to capture and store the sun's energy to later be released as heat. Isolated gain uses a space remote from the primary building space to collect solar energy and then allows the warmer air to naturally flow through. The goal of all of these designs is to collect and store solar energy in the form of heat in the winter and reject solar heat in the summer [2]. It is called passive design because it involves no use of mechanical or electrical devices. Passive solar heating designs are only successful if an accurate analysis of the building location and climate has been performed. Variables that must be taken into consideration include: latitude, sun path, insolation, seasonal variations, shading, wind, and humidity. An example of passive solar space heating can be seen below in Figure 2.

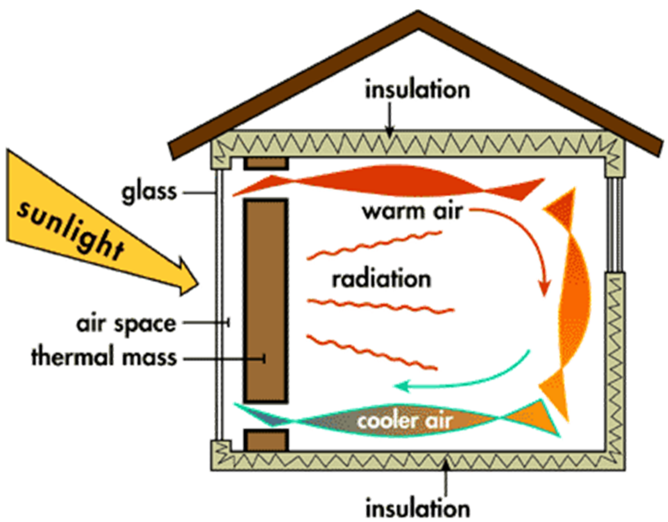


Figure 2. Passive solar space heating design.
http://www.iklimnet.com/save/passive_solar_heating.html

Active Solar Space Heating

Active solar space heating uses collectors to absorb solar radiation in either liquid or air. Air-based systems use fans to distribute the heat that is collected and liquid-based systems use pumps. Active systems also have an energy storage system that is used to provide heat when the sun is not out [2].

Liquid-based space heating systems use solar collectors to capture solar energy. The most common solar collector for commercial buildings is a flat plate solar collector because it is the most efficient. Two other, less common types, are evacuated tube collectors and linear concentrating collectors because they can operate at high temperatures. Flat plate solar collectors use a heat transfer fluid flowing through a pipe to absorb the sun's radiation. The heat transfer fluid is typically water or an antifreeze solution. A pump controls the flow of the water so that the increase in the fluid's temperature can be controlled. The fluid is then sent to a water storage tank system. In this system, a heat exchanger is used to transfer the heat from the heat transfer fluid to the water in the storage tank [6]. The energy harnessed from the sun is sometimes not enough to heat the water to a temperature high enough to heat the entire building, so a supplemental boiler is used to heat the water to the desired temperature. Using the solar energy to preheat the water saves a lot of energy and allows for a significant reduction in the boiler size. The hot water can then be pumped through hot water baseboards or heating coils in fan terminal units and air handlers to heat the building [7]. Figure 3 shows an active, liquid-based solar space heating system.

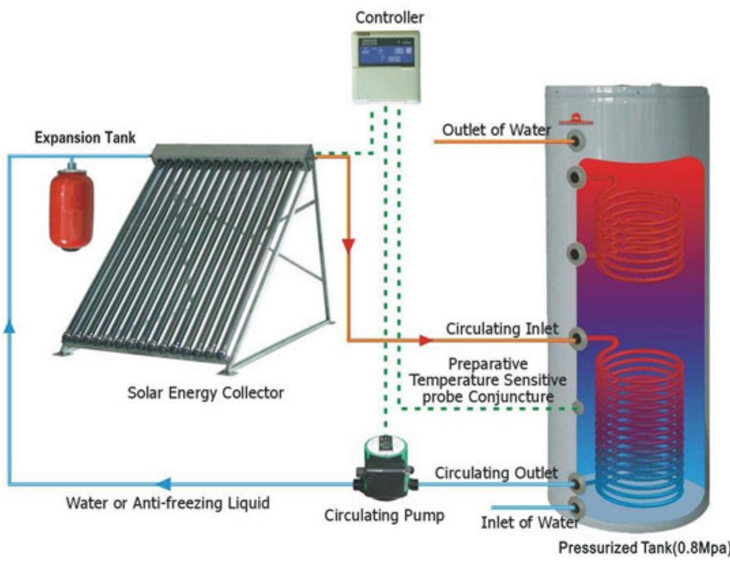


Figure 3. An active liquid-based solar heating system.
http://cleangreenenergyzone.com/active-solar-heating-systems/

Air-based solar space heating systems use air as the heat transfer fluid to capture the sun's solar energy [8]. This can be done in either a closed loop system or an open loop system. In a closed loop system, the collector draws cool return air in from the building and then returns it via fans at a higher temperature after it has been heated due to the solar energy. In an open loop system, the solar collector is used to preheat the incoming outdoor air before it enters the air handler where it is heated again to the desired temperature via an electric coil or gas furnace [6]. Preheating the air allows for a smaller temperature difference between the outside air temperature and desired air temperature, which saves energy. Figure 4 shows an active, air-based solar space heating system.

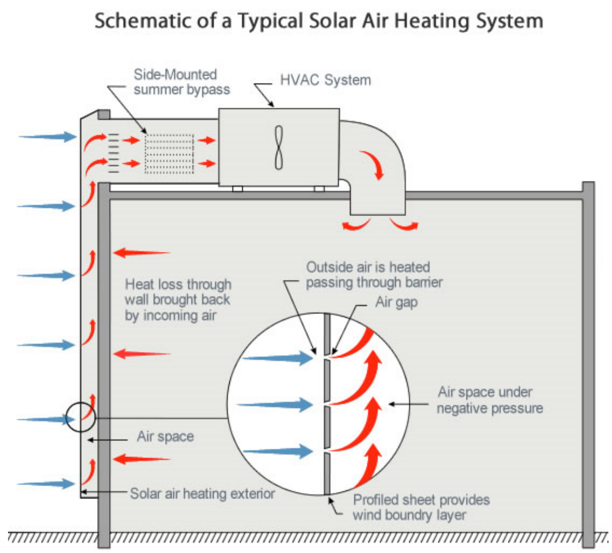


Figure 4. Open loop air-based solar heating system.
http://www.seia.org/research-resources/solar-heating-cooling-energy-secure-future

Active Solar Space Heating System: St. Louis, MO vs. Phoenix, AZ

This report will now compare the installation of an active solar heating system in St. Louis, Missouri to a system in Phoenix, Arizona. This will be done by comparing the peak heating demands of two identical commercial office buildings in each location and the amount of solar energy that can be harnessed in each location on that peak day. For this analysis it is assumed that the peak heating day for both buildings is January 17^{th} and the hour is 1:00pm. The building heating loads were calculated using TRACE 700 and can be seen in Attachment 2 [9]. The building being analyzed is a 20,000 square foot office building with three floors (60,000 total square feet.) Each floor has a height of 15 feet and has 4 feet tall windows all along its perimeter. A sketch of the proposed building is seen in Attachment 1. The south facing wall is 200 feet in length and has a total area of 9,000 square feet. Of the 9,000 square feet, 5,800 square feet have vertical, flat plate solar collectors installed.

The peak heating demand for the office building in St. Louis is 313.9 kW. The load calculations for St. Louis are based on a 0°F outside air temperature and a 70°F inside temperature. The peak heating demand for the building in Phoenix is 160.2 kW. The load calculations for Phoenix are based on a 34° outside air temperature and a 70°F inside temperature [9]. A list of assumptions and all calculations can be seen in Attachments 1, 2, and 3. The results of the analysis can be seen below in Table 1.

	Calculated Heating Demand (kW)	Collected Solar Energy (kW)	Percentage of Demand Covered by Solar Energy
St. Louis	313.9	104.2	33.2%
Phoenix	160.2	465.8	290.8%

Table 1. Comparison of calculated heating demand and collected solar energy for each city.

In Table 1, it is seen that for St. Louis, MO the heating demand at 0°F for the proposed building is 313.9 kW. At 1:00pm on January 17th and an outdoor temperature of 0°F, the proposed solar collectors can collect 104.2 kW of energy. 104.2 kW covers only 33.2% of the building's heating demand. Thus, a large amount of energy from other equipment would still be necessary to effectively heat the building. An economic analysis of the installation of the proposed solar collectors in St. Louis, MO would most likely yield a result of a fairly long economic payback period. The solar collectors would not produce enough energy to pay themselves off in a reasonable amount of time because St. Louis does not receive enough solar energy.

In Table 1, it is seen that for Phoenix, AZ the heating demand at 34°F for the proposed building is 160.2 kW. At 1:00pm on January 17th and an outdoor temperature of 34°F, the proposed solar collectors can collect 465.8 kW of energy. 465.8 kW covers 290.8% of the building's heating demand. Thus, the solar collectors would provide enough energy to effectively heat the entire building with energy to spare. The leftover energy can be converted into electricity to power other building equipment such as lights, computers, or the air conditioning equipment. If the solar collectors were to produce enough energy to sustain the entire building, any additional energy can be converted to electricity and sold to the grid. An economic analysis of the installation of the proposed solar collectors in Phoenix, AZ would yield a much faster economic payback period than St. Louis. The solar collectors would most likely provide enough energy to heat the building year round and power much of the building's other needs as well. This directly correlates to the data seen in Figure 1. Phoenix, AZ sees much more solar radiaton that St. Louis, MO because it is significantly closer to the equator and in turn, the sun. Thus, it is concluded that an active solar space heating system is very effective economically and environmentally if installed in the correct location. An active solar system can be installed in any location and still help the environment. However, no building owner will pay for a system that will not benefit them economically.

Conclusion

HVAC systems in commercial buildings consume a substantial amount of energy. This energy is provided by natural gas or electricity, both of which pollute our environment. The world's energy consumption will continue to rise and we must turn to clean, renewable energy resources before our environment is damaged beyond repair. Solar energy has the potential to be a huge part of the movement towards clean, renewable energy resources. Solar energy can be harnessed using active or passive solar systems. However, solar energy is still relatively expensive and is more economical in some locations than others. The peak heating demand in winter for the commercial building analyzed in this report was 313.9 kW and 160.2 kW for St. Louis and Phoenix, respectively. By adding 5,800 square feet of flat plate solar collectors to the south facing wall of each building, solar energy can supply 33.2% and 290.8% of the building's heating load for St. Louis and Phoenix, respectively. From this data it can be concluded that solar energy is much more effective in Phoenix, AZ than St. Louis, MO. However, solar technology continues to improve each day and will play a huge role in movement of renewable energy resources.

References

[1] "Energy-Efficient HVAC Systems for Commercial Buildings." *Navigant Research*. Navigant, 10 Jan. 2017. Web. 05 June 2017. <https://www.navigantresearch.com/research/energy-efficient-hvac-systems-for-commercial-buildings>.

[2] "Solar Space Heating and Cooling." *Goldkamp Heating & Cooling*. U.S. Department of Energy, n.d. Web. 05 June 2017. <http://www.goldkamphvac.com/webapp/p/338/solar-space-heating-and-cooling>.

[3] "The History of Solar." *Energy Efficiency and Renewable Energy* (n.d.): n. pag. U.S. Department of Energy. Web. <https://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf>.

[4] Reece, Will. "The History Of Solar Power." *Experience*. N.p., n.d. Web. 05 June 2017.<https://www.experience.com/alumnus/article?channel_id=energy_utilities&source_page=additional_articles&article_id=article_1130427780670>.

[5] Duffie, John A., and William A. Beckman. *Solar Engineering of Thermal Processes*. Chichester: John Wiley & Sons, 2013. Print.

[6] "Solar Space Heating." *Solar Energy at Home*. N.p., n.d. Web. 05 June 2017. <http://www.solar-energy-at-home.com/solar-space-heating.html>.

[7] "Active Solar - Space Heating and Domestic Hot Water." *Strawbale Farms*. N.p., n.d. Web. 05 June 2017. <http://www.strawbalefarms.com/resources/other-resources/active-solar/>.

[8] "Solar Heating & Cooling." *SEIA*. Solar Energy Industries Association, n.d. Web. 05 June 2017. <http://www.seia.org/policy/solar-technology/solar-heating-cooling>.

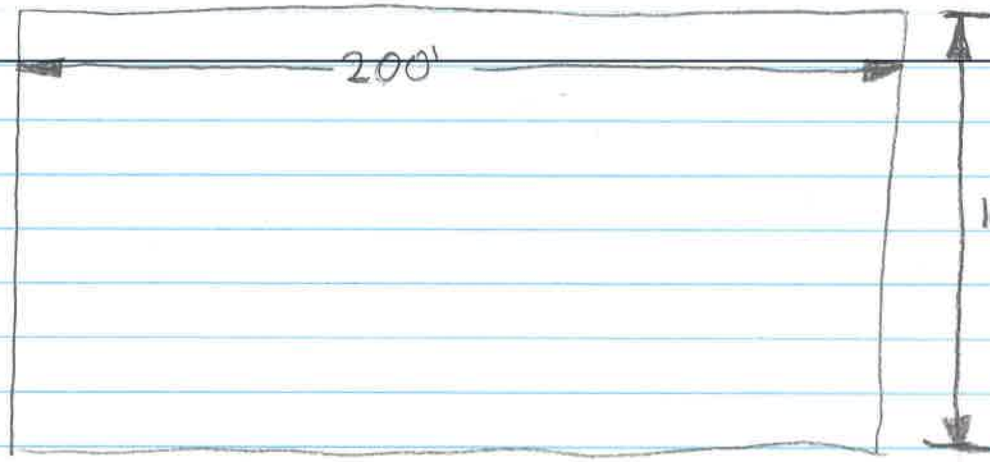
[9] TRANE: Heating and Air Conditioning Services & Systems. *TRACE 700*. Computer software. Vers. 6.3.3. N.p., n.d. Web.

[10] Rosenstein, Peter D. "Solar Power Today and Its Potential for the Future." *The Huffington Post*. TheHuffingtonPost.com, 14 Sept. 2015. Web. 05 June 2017. <http://www.huffingtonpost.com/peter-d-rosenstein/solar-power-today-and-its_b_8134790.html>.

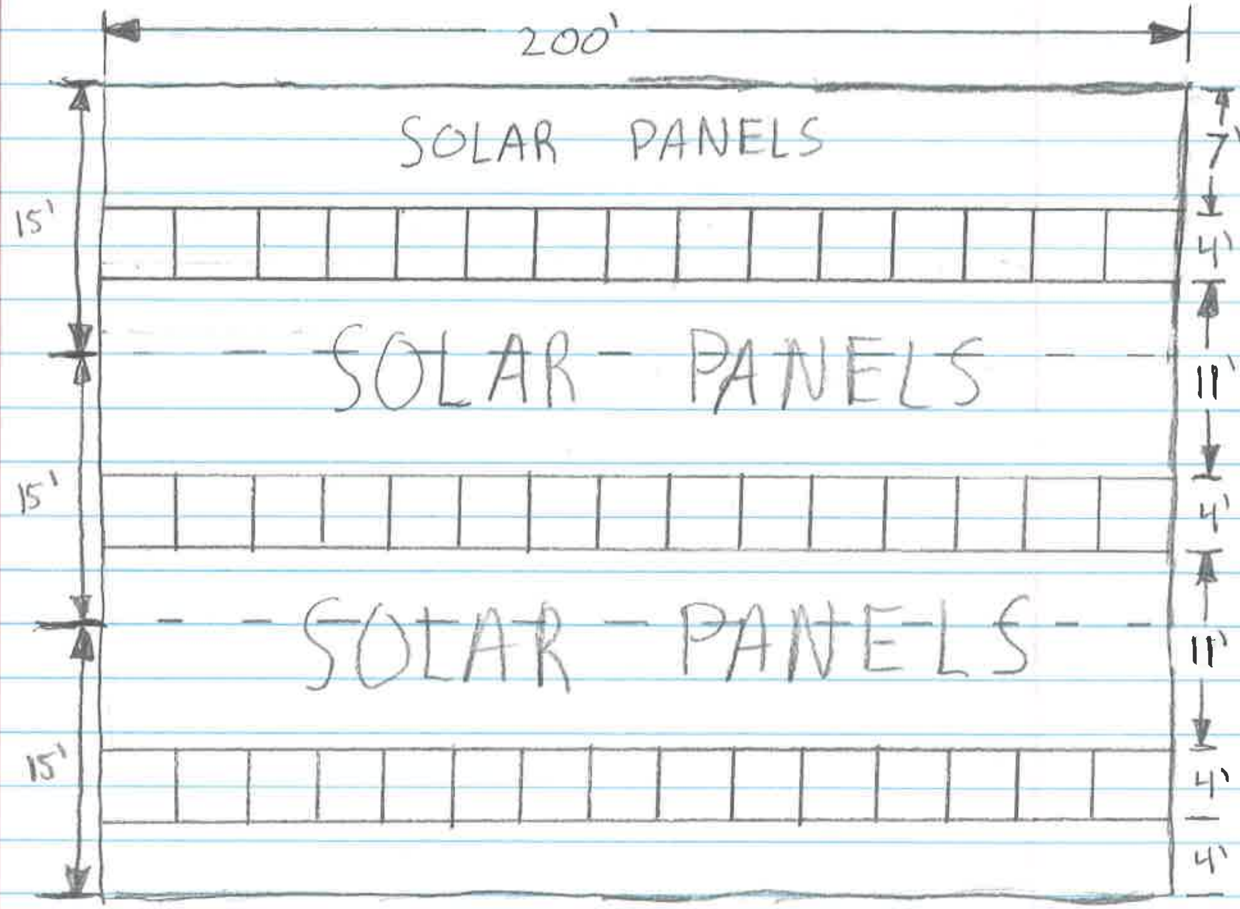
Assumptions

3 stories, each 200ft x 100ft, General office building

Floor Plan



South wall



System Checksums

AHU-STL — Single Zone Variable Air Volume

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 7 / 15; Outside Air: OADB/WB/HR: 95 / 78 / 120

Clg Space Peak — Mo/Hr: 8 / 15; OADB: 95

	Space Sens. + Lat. Btu/h	Plenum Sens + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	113,858	113,858	7	0	0
Glass Solar	193,215	0	193,215	12	221,908	24
Glass/Door Cond	68,968	0	68,968	4	68,069	7
Wall Cond	36,558	27,642	64,200	4	38,354	4
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	185,192		185,192	12	64,855	7
Sub Total ==>	483,932	141,500	625,432	40	393,185	42
Internal Loads						
Lights	184,302	122,868	307,170	20	184,302	20
People	135,000	0	135,000	9	75,000	8
Misc	204,780	0	204,780	13	204,780	22
Sub Total ==>	524,082	122,868	646,950	42	464,082	50
Ceiling Load	74,529	-74,529	0	0	71,155	8
Ventilation Load	0	0	314,827	20	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-34,687	-34,687	-2		
Sup. Fan Heat			0	0		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	1,082,543	155,152	1,552,522	100.00	928,422	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design; OADB: 0

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	-105,257	9.82
Glass Solar	0	0	0.00
Glass/Door Cond	-255,389	-255,389	23.83
Wall Cond	-60,480	-107,846	10.06
Partition/Door	0	0	0.00
Floor	-21,000	-21,000	1.96
Adjacent Floor	0	0	0
Infiltration	-229,400	-229,400	21.41
Sub Total ==>	-566,269	-718,891	67.09
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-80,121	0	0.00
Ventilation Load	0	-389,980	36.39
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		37,290	-3.48
OA Preheat Diff.		0	0.00
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-646,390	-1,071,581	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	116.4
Ra Plenum	78.9	65.8
Return	78.9	65.8
Ret/OA	80.9	39.5
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.0	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	42,495	12,749
Terminal	42,495	12,749
Main Fan	42,495	12,749
Sec Fan	0	0
Nom Vent	5,100	5,100
AHU Vent	5,100	5,100
Infil	3,000	3,000
MinStop/Rh	12,749	12,749
Return	45,495	15,749
Exhaust	8,100	8,100
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	12.0	40.0
cfm/ft²	0.71	0.21
cfm/ton	328.46	
ft²/ton	463.76	
Btu/hr·ft²	25.88	-17.86
No. People	300	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	129.4	1,552.5	1,169.5	41,327	80.9	65.1	69.6	55.0	52.5	56.2
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	129.4	1,552.5								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	60,000		
Part	0		
Int Door	0		
ExFlr	600		
Roof	20,000	0	0
Wall	27,000	7,200	27
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-1,071.6	12,749	39.5	116.4
Aux Htg	0.0	0	0.0	0.0
Preheat	0.0	0	0.0	0.0
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-1,071.6			

System Checksums

AHU-PHOENIX — Single Zone Variable Air Volume

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 7 / 15; Outside Air: OADB/WB/HR: 107 / 71 / 61

Clg Space Peak — Mo/Hr: 9 / 15; OADB: 97

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	143,238	143,238	10	0	0
Glass Solar	183,960	0	183,960	13	277,595	28
Glass/Door Cond	111,959	0	111,959	8	76,655	8
Wall Cond	45,855	35,184	81,039	6	44,752	4
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	120,613		120,613	8	70,497	7
Sub Total ==>	462,388	178,423	640,810	44	469,499	47
Internal Loads						
Lights	184,302	122,868	307,170	21	184,302	18
People	135,000	0	135,000	9	75,000	7
Misc	204,780	0	204,780	14	204,780	20
Sub Total ==>	524,082	122,868	646,950	44	464,082	46
Ceiling Load	79,959	-79,959	0	0	70,831	7
Ventilation Load	0	0	205,042	14	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-36,388	-36,388	-2		
Sup. Fan Heat			0	0		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	1,066,429	184,943	1,456,415	100.00	1,004,412	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design; OADB: 34

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	-54,227	9.92
Glass Solar	0	0	0.00
Glass/Door Cond	-133,005	-133,005	24.33
Wall Cond	-31,104	-55,506	10.15
Partition/Door	0	0	0.00
Floor	-10,800	-10,800	1.98
Adjacent Floor	0	0	0
Infiltration	-115,358	-115,358	21.10
Sub Total ==>	-290,268	-368,897	67.47
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-40,076	0	0.00
Ventilation Load	0	-196,109	35.87
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		18,238	-3.34
OA Preheat Diff.		0	0.00
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-330,343	-546,769	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	91.9
Ra Plenum	79.2	67.9
Return	79.2	67.9
Ret/OA	82.3	55.7
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.0	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	47,057	14,123
Terminal	47,057	14,123
Main Fan	47,057	14,123
Sec Fan	0	0
Nom Vent	5,100	5,100
AHU Vent	5,100	5,100
Infil	3,000	3,000
MinStop/Rh	14,123	14,123
Return	50,057	17,123
Exhaust	8,100	8,100
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	10.8	36.1
cfm/ft²	0.78	0.24
cfm/ton	387.72	
ft²/ton	494.36	
Btu/hr·ft²	24.27	-9.11
No. People	300	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	121.4	1,456.4	1,347.6	46,266	82.3	61.7	52.9	55.0	50.4	49.3
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	121.4	1,456.4								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	60,000		
Part	0		
Int Door	0		
ExFlr	600		
Roof	20,000	0	0
Wall	27,000	7,200	27
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-546.8	14,123	55.7	91.9
Aux Htg	0.0	0	0.0	0.0
Preheat	0.0	0	0.0	0.0
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-546.8			

South Wall:

Total Wall Area = 9000 ft^2

Window Area = 2400 ft^2

Plain Wall Area = 800 ft^2

Solar Panel Area = 5800 ft^2

January 17, 1:00 PM

	St. Louis	Phoenix
	$T_a = 0°F$	$T_a = 34°F$
	$\rho_g = 0.7$	$\rho_g = 0.3$
Heating Demand:	313.9 KW	160.2 KW

Collectors $A_c = 5800 ft^2 = 538.84 m^2$

$U_L = 6 \frac{W}{m^2 - °C}$, $F' = 0.87$, $F'' = 0.88$, $F_R = 0.77$

$(\tau\alpha)_b = 0.82$, $(\tau\alpha)_d = 0.73$, $(\tau\alpha)_g = 0.63$

$T_{fi} = 60°C$

St. Louis, MO

1:00 PM $\Rightarrow \omega = 15°$

$\phi = 38.6°$, January 17, $n = 17$, $\beta = 90°$

$\delta = 23.45 \sin\left(360 \cdot \frac{n+284}{365}\right) \Rightarrow \delta = -20.9°$

$\cos \omega_s = -\tan\phi \tan\delta \Rightarrow \cos\omega_s = -\tan(38.6)\cdot\tan(-20.9)$

$\omega_s = 72.25°$

From Table 1.10.1 $\Rightarrow \bar{H}_o = 16.14 \frac{MJ}{m^2}$

$$H_o = \frac{(24)(3600)G_{sc}}{\pi}\left(1 + .033\cos\left(\frac{360n}{365}\right)\right) \times \left(\cos\phi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right)$$

$H_o = 16.08 \frac{MJ}{m^2}$ $\qquad G_{sc} = 1367 \frac{W}{m^2}$

From Appendix D $\Rightarrow \bar{K}_T = 0.43$ (used Springfield, IL)

Assume $K_T = 0.43$ for January 17.

$$\frac{H_d}{H} = 1.0 - 0.2727K_T + 2.5557K_T^2 - 11.9514K_T^3 + 9.3879K_T^4$$

$\Rightarrow \frac{H_d}{H} = 0.726$

$K_T = \frac{H}{H_o} \Rightarrow H = (.43)(16.08) \Rightarrow H = 6.91 \frac{MJ}{m^2}$

$H_d = (.726)(6.91) \Rightarrow H_d = 5.02 \frac{MJ}{m^2}$

$H = H_d + H_b \Rightarrow H_b = 1.89 \frac{MJ}{m^2}$ $\qquad \phi - \beta = -51.4$

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\cos\omega + \sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta} \Rightarrow R_b = \frac{.842}{.483} \Rightarrow R_b = 1.743$$

STL

$K_T = 0.43$ $\qquad K_T = \frac{I}{I_o}$

$\frac{I_d}{I} = .9511 - .1604\, K_T + 4.388\, K_T^2 - 16.638\, K_T^3 + 12.336\, K_T^4$

$\frac{I_d}{I} = 0.7924$

$a = .409 + .5016 \sin(\omega_s - 60) = .5154$

$b = .6609 - .4767 \sin(\omega_s - 60) = .5598$

Eqn (2.13.2)

$r_t = \frac{\pi}{24}(a + b\cos\omega) \frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi\,\omega_s}{180}\cos\omega_s} = 0.161$

$r_t = \frac{I}{H} \Rightarrow I = (.161)(6.91) \Rightarrow \underline{I = 1.11 \ \frac{MJ}{m^2}}$

$I_d = (.7924)(1.11) \Rightarrow \underline{I_d = 0.881 \ \frac{MJ}{m^2}}$

$I = I_b + I_d \Rightarrow \underline{I_b = 0.229 \ \frac{MJ}{m^2}}$

$I_o = \frac{1.11}{.43} \Rightarrow \underline{I_o = 2.58 \ \frac{MJ}{m^2}}$

Assume $\rho_g = 0.7$

$A_c = 5800\ ft^2 = 538.84\ m^2$

$Q_u = A_c\left[S - U_L(T_{pm} - T_a)\right] = A_c F_R\left[S - U_L(T_{fi} - T_a)\right]$

$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \left(\frac{1+\cos\beta}{2}\right) + \rho_g I (\tau\alpha)_g \left(\frac{1-\cos\beta}{2}\right)$

STL

$F' = .87 \quad F'' = .88$

$F_R = 0.77 \quad T_{fi} = 60°C$

Assume: $U_L = 6 \frac{W}{m^2 \cdot °C}$ $(\tau\alpha)_b = .82$ $(\tau\alpha)_d = .73$ $(\tau\alpha)_g = .63$

$T_a = 0°F = -17.78°C = 255.37K$

$S = (.229)(1.743)(.82) + (.881)(.73)\left(\frac{1+\cos 90}{2}\right) + (.7)(1.11)(.63)\left(\frac{1-\cos 90}{2}\right)$

$S = 0.894 \frac{MJ}{m^2}$

$Q_u = A_c F_R [S - U_L (T_i - T_a)]$

$Q_u = (538.84)(.77)[(900)(.894) - (6)(60 + 17.78)]$

$Q_u = 104205 W$

$\boxed{Q_u = 104.2 KW}$

Phoenix, AZ

1:00 PM ⇒ $\omega = 15°$

$\phi = 33.4°$, January 17, $n = 17$, $\beta = 90°$

$\delta = 23.45 \sin\left(360 \cdot \frac{n+284}{365}\right) \Rightarrow \delta = -20.9°$

$\cos\omega_s = -\tan(33.4)\cdot\tan(-20.9) \Rightarrow \omega_s = 75.42°$

From Table 1.10.1 ⇒ $\overline{H}_o = 19.26 \frac{MJ}{m^2}$

From Appendix D ⇒ $\overline{H} = 11.60 \frac{MJ}{m^2}$ $\overline{K}_T = 0.60$

Assume $K_T = 0.60$ for January 17

$$H_o = \frac{(24)(3600)(G_{sc})}{\pi}\left(1 + .033\cos\left(\frac{360n}{365}\right)\right) \times \left(\cos\phi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right)$$

$H_o = 19.25 \frac{MJ}{m^2}$

$H = K_T \cdot H_o = (.60)(19.25) \Rightarrow H = 11.55 \frac{MJ}{m^2}$

$$\frac{H_d}{H} = 1.0 - .2727K_T + 2.5557K_T^2 - 11.9514K_T^3 + 9.3879K_T^4$$

$\frac{H_d}{H} = 0.3916 \Rightarrow H_d = (.3916)(11.55) \Rightarrow H_d = 4.52 \frac{MJ}{m^2}$

$H = H_b + H_d \Rightarrow H_b = 7.03 \frac{MJ}{m^2}$ $\phi - \beta = -56.6°$

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\cos\omega + \sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta} \Rightarrow R_b = \frac{.795}{.557}$$

$R_b = 1.427$

PHNX

$K_T = 0.60 \qquad K_T = \frac{I}{I_o}$

$\frac{I_d}{I} = .9511 - .1604\,K_T + 4.388\,K_T^2 - 16.638\,K_T^3 + 12.336\,K_T^4$

$\frac{I_d}{I} = 0.4395$

$a = .409 + .5016\sin(\omega_s - 60) = 0.5424$

$b = .6609 - .4767\sin(\omega_s - 60) = 0.534$

$r_t = \frac{\pi}{24}(a + b\cos\omega)\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s} = 0.1554$

$r_t = \frac{I}{H} \Rightarrow I = (.1554)(11.55) \Rightarrow I = 1.80\ \frac{MJ}{m^2}$

$I_d = (1.80)(.4395) \Rightarrow \underline{I_d = 0.79\ \frac{MJ}{m^2}}$

$I = I_b + I_d \Rightarrow \underline{I_b = 1.01\ \frac{MJ}{m^2}}$

$I_o = \frac{1.80}{.6} \Rightarrow \underline{I_o = 3\ \frac{MJ}{m^2}}$

Assume $\rho_g = 0.3$

$A_c = 5800\,ft^2 = 538.84\,m^2$

$Q_u = A_c F_r [S - U_L(T_{fi} - T_a)]$

$S = I_b R_b (\tau\alpha)_b + I_d(\tau\alpha)_d\left(\frac{1+\cos\beta}{2}\right) + \rho_g I(\tau\alpha)_g\left(\frac{1-\cos\beta}{2}\right)$

PHNX

Assume: $U_L = 6 \frac{W}{m^2 \cdot °C}$, $(\tau\alpha)_b = .82$, $(\tau\alpha)_d = .73$, $(\tau\alpha)_g = .63$

$F_R = .77$, $F' = .87$, $F'' = .88$

$T_a = 34°F = 1.11°C = 274.26K$

$S = (1.01)(1.427)(.82) + (.79)(.73)(.5) + (.3)(1.80)(.63)(.5)$

$S = 1.64 \frac{MJ}{m^2}$

$Q_u = (538.84)(.77)\left[(900)(1.64) - (6)(60 - 1.11)\right]$

$Q_u = 465799.27 \ W$

$Q_u = 465.8 \ KW$