Energy efficiency in buildings: challenges and solutions

ME 613 TERM PAPER

by

Adarsh Sharma, Dhananjay Chimnani, Chinmay Pratap

DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

October 2024

Contents

List of Figures

List of Tables

1 The Building Sector's Energy Challenge: Rising Consumption and Emissions

Across the globe, the building industry consumes about 54% of all electricity, more than any other sector. This is a big number, given that people spend more than 90% of their time in these structures. The size and quantity of buildings in metropolitan areas are expected to rise due to the fast urbanisation, especially in developing nations, which would raise demand for electricity and other energy sources used in buildings. Africa is witnessing a notable increase of its urban landscape and population density, with the continent having the greatest annual rate of urbanisation in the world, at 4.3%. There are already 70 African cities with a population of one million or more, and by 2040, there should be ninety. In case of Asia where there are 112 cities with 1 million plus inhabitants and these cities are rapidly constructing buildings which clearly indicates that this figure of 54% will increase in the coming future.

There are many countries where the consumption of buildings electricity is even more than the transport industry. The climate change and consumption of electricity is chain of cycle one is the reason of increasing the other one and to break this we need to manage our electric consumption. It is true that many other sectors involve in contributing towards climate changes and these all sectors are needed to be improved and we can achieve a sustainable way of development. In this paper, we will particularly focus on the energy consumption, environmental damages caused by the building sector in the world.

As we can see that urbanization in the continents is way more higher and thus more mega-cities will be developed and it is high time to reunite countries and discuss the planning of these mega-cities brought out in more structured way so that more energy efficient buildings can be constructed and loss of energy can be reduced. Society have to make renewable sources of energy as a primary energy source and it has to be developed so that it can be cost-efficient as well.

With increasing electricity demand and exhaustion of the non renewable resources there is a big need to shift on some other resources. Although renewable sources of electricity such as hydro, geothermal or wind provide electricity at a much lower cost, their capital outlay is large, they are complex and take much longer to implement. On the other hand the construction and maintaining the cooling of these buildings releases many greenhouse gases which are the major contributors of global warming and climate changes. It is expected that around 2040 the sea level would be increased by 5 inches which will directly affect the coastal areas.

The building sector encompasses a diverse set of end use activities, which have different energy use implications. Space heating, space cooling and lighting, which together account for a majority of building energy use in industrialized countries, depend not only on the energy efficiency of temperature control and lighting systems, but also on the efficiency of the buildings in which they operate. Building designs and materials have a significant effect on the energy consumed for a select set of end uses.

2 Enhancing Building Energy Efficiency: Current Methods and Implementation

As mentioned in previous section clearly states that developing countries should focus on making building's more energy efficient. In this section, we will take a look what exactly does energy efficient buildings are and how they different from the buildings that are constructed these days. So energy efficiency of a building is the extent to which the energy consumption per square metre of floor area of the building measures up to established energy consumption benchmarks for that particular type of building under defined climatic conditions.

It is very crucial to highlight why we are focusing on energy efficient systems in buildings that are used for heating and cooling the building :

- **Energy loss:** The energy that we uses to cool and to some extent heat the rooms in the buildings doesn't have any appreciable efficiency. It is 30% to 40% efficient which makes around 70% of the input energy as a waste.
- **Limited Energy resources:** Both the renewable and non renewable energy sources have some drawbacks, which limits our energy source's and we cannot afford to waste them.
- **Increasing Efficiency:** To save energy and get the most out of the resources available, we need to build systems and structures that use energy more efficiently.

Some methodology we can use and that are advised by experts for making energy efficient buildings:

- **Natural Energy gains:** Passive heating and cooling using day sunlight and ventilation respectively. By using such methods the consumption on the AC plants and heaters could be reduced. This includes making the buildings in such a shape and modifying its orientation and form which uses best use of sunlight and the natural flow of air in the city, city planning should be done in a through way to implement such changes. Effective use of natural daylight combined with the avoidance of glare and unwanted solar gains. When it comes to building designs, the first and of utmost importance is to give priority to the natural ventilation to create airflow and diminish the need for artificial cooling and heating. Besides that, mechanical fans are applicable in that way. The use of these devices will thereby ensure good air movement throughout the room. By using both natural and mechanical ventilation, we will make the air clean and energy efficient and we will reach the goal of saving the energy of the building as a whole.
- **Phase changing material :** These are special materials which are naturally and artificially produced and these materials change there physical characteristics when we change the temperature and moisture in the surrounding environment. PCM's enable the principles of thermal mass to be applied to lightweight buildings and building elements without affecting the major benefits of the system approach. This point is being discussed in detail in the later section in this paper.

- **Internal heat gains :** Internal heat is the thermal energy from people, lighting and appliances that give off heat to the indoor environment. While this is desirable in cold weather as it reduces the energy requirements for heating, in hot weather it increases the energy required for cooling.

- **Improving the insulation of the building's fabrics :** To make the flow of heat more insulated so that in summers the cooled room does't absorb heat rapidly from the outer surface. This can be achieved by carpets for floor and good heavy curtains to prevent conduction of heat. However, these temporary measures should be seen as such, that they can be eliminated or changed to retain heat during winter and thus make the room warmer. This kind of flexibility fosters different types of energy saving solutions that are capable of adjusting to seasonal variations, thus, a building can keep the comfort of people and use energy effectively all year round.

- **Reducing cooling demand :** Energy use in typical air-conditioned office buildings is approximately double that of naturally ventilated office buildings. The need for air-conditioning or the size of the systems installed can be reduced by controlling solar gains through glazing, reducing lighting loads and installing effective lighting controls.

- **Preheating:** or pre-cooling of the fresh ventilated air by natural thermal resources is a specific method for energy efficient houses. In this way, the load of dedicated equipment of heating or cooling is reduced.

- **Low-E layers on the glass:** Currently, the design of energy efficient houses includes windows with "Low-E" layers on both sides of the glass. In the summer, when the outside air temperature is greater than the inside one, the exterior Low-E layer does not allow passing of thermal radiation and by reflecting it, reduces the solar heat gains. In the winter, the Low-E coating on the opposite side reflects the thermal radiation reducing the heat loss to outside (in this way the inner surface of the glass has a higher temperature than a normal glass). Depending on the building orientation, thus on the angle of radiation incidence, some optical properties can be assigned to the glass layer. This method are used in Finland to make the habitat of humans more comfortable.

It is well known that global reduction of CO2 and other greenhouse gases emissions plays a vital part in diminishing the climate changes. A decrease of the energy consumption in the most important fields is the main solution to reduce the greenhouse gas emissions directly. The European Directive approved in 2007 set three goals taking as a reference year 1990: to lower the emissions with 20%, to raise the energy production from renewable's with 20% and to improve the energy efficiency with 20% [7].

3 Passive House Principles: An Approach to Energy Conservation

3.1 History and Context

It has been seen historically that humans come up with new methods and techniques to maintain their desired level of comfort. An example of this can be the ancient houses built in the region of Carpathians, where people came up with the idea of making partially buried houses to keep the indoor temperature stable [5]. Another example is of Romans, who used the heating produced by burning gases when passed through the cavities in the walls. But these structures were not based on any scientific calculations and simulations [5]. They were based on the previous knowledge and experiences. The idea of passive houses came into picture in the 1960's when researchers taking the examples of these simple historically built structures, tried to replicate the same for the houses in Europe to meet the high energy requirements and reduce the discomfort caused due to the extreme winters [1].

In the 1960s, research on highly insulated buildings was carried out, which helped Sweden develop more energy-efficient buildings compared to the rest of Europe [1]. Further developments in insulation, thermal bridges, ventilation, and air tightness—important concepts in this subject—were also explored [1]. Simultaneously, efforts were made to measure all the heat gains and losses from buildings and to calculate the energy requirements after net heat gains had been exploited. Passive houses were defined as: "buildings which have an extremely small heating energy demand even in the Central European climate and therefore need no active heating. Such houses can be kept warm passively by using the existing internal heat sources and the solar energy entering through the windows, as well as by the minimal heating of incoming fresh air." The first test project, a passive house apartment block, was funded and built in Germany. Results over the past 20 years have shown that this project achieved 90% annual energy savings compared to the German Building Code of 1995 [1].

3.2 Concept Behind the Passive Houses

Passive house is basically a building standard developed to help build structures having very minimal energy requirements (above the net heat gains) compared to the trivial buildings. According to the present standard, they do not require more than 15 KWh of useful heat per year and square meter of living area for space heating [3]. This standard has been made keeping in mind that the comfort is not compromised. In the case of passive houses, substantial amounts of solar radiation is trapped by the help of large windows on the south-facing side; also, this trapped heat is not allowed to leave using a triple low-e glazing with noble gas filling. The low emissivity value helps to reduce the losses due to radiation from the enclosure.

The heat loss is further reduced by using highly thermally insulating materials to construct the enclosure. Another way can be to increase the thickness of insulation (thermal resistance is directly proportional to the length perpendicular to the direction of heat flow). It can be made from polystyrene, wood, or mineral fibres, or from foam boards. The pipes carrying cold water are insulated so that there are no heat losses due to condensation.

Now, after the temperature has been made stable, we focus on the ventilation of the house. For ventilation, stale air from the kitchen and the bathrooms is extracted while the fresh air flows into the living area. But, allowing the fresh air flow without any processing will lead to unwanted heat losses in winters and unwanted heat gains in the summers. To prevent this, the fresh air that enters exchanges heat with the stale air leaving the house. Therefore, a ventilation system with heat recovery is very important for passive houses. This helps to keep comfortable temperatures and excellent air quality within the enclosure.

The enclosure is made airtight to prevent air from escaping through cracks and voids in the building's construction. For this the we make sure that the air leakage through the construction material of a passive house is approximately 5% of the air leakage taking place in a normal building [3]. During winters, if the enclosure is not airtight, cold air through cracks can lower the local temperatures of some sections of the enclosure, which can cause discomfort. These unwanted streams of cold air are called cold draughts. To make sure that the enclosure is airtight, air tests should be taken at the time of construction to detect and remove these voids. Airtightness also makes sure that majority of air entering the enclosure first passes through the heat recovery system. Heat from the warm waste water leaving the enclosure is also extracted. This is done by a storage tank, which puts this extracted energy back into the enclosure. This helps to further minimize the heat losses.

3.3 Construction and Designing of Passive Houses

For designing the enclosure, it is a good idea to simulate the enclosure and ambient conditions using software like PHPP (Passive house planning package) or DYNBIL (Dynamic Building Simulation Software) to do an energy analysis [3]. PHPP helps in static modeling while DYNBIL helps in dynamic modeling. Using them, quantities like energy demand, heat loss, and heat gain can be calculated for different ambient and enclosure settings. The only problem in using simulations is that it requires a large dataset to give reliable results.

Next, the enclosure should be insulated at all the surfaces which are in direct contact with the ambient with a thick insulation layer of a highly insulating material. An airtight layer should be made around the enclosure as most of the insulating materials do not provide airtightness.

Designing the windows is a major step as most of the heat losses take place through the windows. In passive houses, low-emissivity glazing is used to reduce the radiative loss. Spaces in a window are filled with a noble gas to reduce the heat loss due to convection and conduction. Windows should be large on the side facing the south, this traps heat from the sunlight which helps to keep the room warm during the winters.

Thermal bridges should be eliminated during the design process. Thermal bridges are regions in the enclosure where the heat flow is quite high compared to the surrounding regions which causes heat losses to the ambient. Thermal bridges can make up to 25% of the total heat loss to the ambient [1]. They are typically found at the junctions of the enclosure walls, near the windows, steel structures used in the balcony, etc. To build a thermal bridge-free building, a systematic procedure called Thermal Triad Method is used. It consists of three steps :

1. **Identification**: Thermal bridges are identified by areas where there is a change in direction (places where walls intersect with each other and with the roof) or material.

2. **Avoidance**: Avoiding any thermal bridges by providing continuous exterior insulation (the insulation of walls, roofs, and floors should be connected) without penetrating it anywhere.

3. **Minimization**: As some thermal bridges cannot be removed, we minimize heat losses through them by introducing thermal breaks.

A mechanical ventilation system which has heat recovery should be built to maintain the quality of the air inside the enclosure. The pipe network carrying the cold water should be insulated so that there is no condensation which will eventually cause heat loss. A storage tank is to be built to extract heat energy from the warm waste water that leaves the enclosure. Shading is the method by which solar radiation entering the windows is reduced using overhangs, trees, fins, etc. They are very useful during the summer season. Details of Passive House construction also depend on the local climate, the shape and orientation of the building layout, the shading situation, etc.

3.4 Phase Change Materials

Phase change materials have been developed to increase the thermal efficiency of buildings. There are three forms in which the thermal energy can be stored:

- Chemical heat (in the form of chemical bonds)
- Sensible heat (heating and cooling)
- Latent heat (phase change)

Out of these three, latent heat thermal energy storage is a better approach as the amount of heat released or absorbed during a phase change process is much higher compared to a sensible heating process. Also, during a phase change process, there is little to no change in temperature, which reduces overall temperature fluctuations and leads to less discomfort. In a PCM, energy is stored when it melts and is released when it solidifies. For example, if the room temperature is above the comfort range, the PCM will melt and absorb heat from the room, bringing the temperature back into the comfort range. Now, if during the night the room temperature falls, the PCM will release the previously absorbed heat back into the room. To use a PCM in buildings, we need to check two main parameters:

- **Appropriate melting temperature:** According to literature a PCM should have the phase change temperature (freezing/melting) in the human comfort zone of 22-26°C [4].

- **Melting heat:** It is the amount of heat released or absorbed by a material during the phase change process. The thermal storage capacity is directly correlated with the melting heat.

One of the efficient methods to increase the thermal efficiency of a building is to mix the PCM with the construction material. This mixing leads to change in the thermal properties of the construction material. This method is called Direct incorporation. This procedure is inexpensive and simple as no extra equipment are required. PCMs can be incorporated in almost every component of the building (walls, ceilings, floor, windows, shutters). Incorporating PCMs in the roof is a good idea as now the PCM will absorb both incoming solar heat and the thermal energy from the ambient. It has been noted that adding PCMs in the floor can be beneficial as the floor has a large surface area which leads to more heat losses, therefore, incorporating a PCM to the floor will help to store this energy. The main disadvantage of Direct incorporation is the leakage of the PCM when it is in the liquid state. This can lower the fire resistance of the material which can have serious implications. To solve this problem, methods like encapsulation and addition of shape stabilized PCM's can be used. A big disadvantage of these methods is the increased complexity and cost of the procedure.

4 Active Measures for Building Energy Efficiency: Innovative Cooling and Heat Recovery Systems

We now look at active measures that could be implemented in current refrigeration systems of buildings to reduce power consumption and make them energy efficient. We will analyze two such methods namely Free cooling and Superheat recovery in chillers.

4.1 Free cooling

A traditional chiller plant is illustrated in fig. 2. In this system, chilled water (CHW) is cooled by transferring heat between condenser water (CW) and refrigerant (REFG) as part of the typical cooling cycle.

In locations where ambient air temperatures are low (at or below +1°C), the chiller water can flow through a cooler instead of passing through the refrigeration unit's evaporator. This arrangement allows the chiller's compressor to be stopped, resulting in significant energy savings, as depicted in fig. 3.

When ambient temperatures rise (up to 7°C), the system operates both the evaporator and the cooler by directing chiller water to each component. In even warmer conditions, such as during summer, the refrigeration unit's condenser is cooled by condenser water flowing through the cooler.

In all scenarios, the refrigeration unit operates with reduced cooling power, which lowers electrical consumption. Consequently, the unit becomes more efficient, increasing its coefficient of performance (COP) and reducing overall economic costs. For example, power consumption is reduced from 165,478 kWh to 41,264 kWh within a temperature range of 1°C to 2.25°C, as presented in Table 1.

Table 1: Power consumption of the refrigeration unit [6]

Ambient air temperature [°C]	**Chiller performance [%]**	**Free cooling time [h]**	**Power consumption with free cooling [kWh]**	**Power consumption without free cooling [kWh]**
Below +1	0.00	1843	0	520,456
+1 to +2.25	23.75	585	41,264	165,478
+2.25 to +3.5	47.50	593	83,657	166,440
+3.5 to +7	71.25	1178	292,280	332,373
Total:		4199	417,202	1,184,747

Calculations : From Table 1, The power consumption of the compressor is reduced to:

$$\text{Reduced Power Consumption} = \frac{647,816.40}{358,300.02} \times 100 = 35.2\% \quad (1)$$

For the entire year, the power consumption of the refrigeration unit is as follows:

- **Currently:** $2,471,634\,\text{kWh/year}$
- **With Free Cooling:** $1,704,088\,\text{kWh/year}$

The reduction in power consumption can be calculated as:

$$\text{Reduction} = \frac{2,471,634.0 - 1,704,088.0}{2,471,634.0} \times 100 = 31.05\% \tag{2}$$

This analysis shows that using free cooling results in a 31.05% annual reduction in power consumed by the refrigeration unit's compressor. Consequently, the estimated energy savings amount to:

$$\text{Estimated Savings} = 767.55\,\text{MWh} \times 466.81\,\text{PLN/MWh} = 358,300.02\,\text{PLN/year} \tag{3}$$

This calculation is based on an average electricity price of 466.81 PLN/MWh (gross).

According to Table 2, the costs associated with upgrading the system to include free cooling, given the exchange rate of 4.20 PLN/EUR, is 647,816.40 PLN. Therefore, the simple payback time (SPBT) can be calculated as:

$$\text{SPBT} = \frac{647,816.40}{358,300.02} \approx 1.81\,\text{years} \tag{4}$$

Table 2: Costs related to upgrading the system to include Free Cooling [6]

No.	Item	Net Value [EUR]	Gross Value [PLN]
1.	Glycol cooler	80,000.00	413,280.00
2.	Control and hydraulics systems	15,000.00	77,490.00
3.	Labour and additional works	30,400.00	157,046.40
Total:		**125,400.00**	**647,816.40**

4.2 Waste superheat recovery

Refrigeration systems are designed to remove heat from interior spaces and reject it to the ambient (outside) air. Although this heat is of low-grade quality, it still represents wasted energy. From an energy conservation perspective, reclaiming this heat in a usable form would be beneficial.

In a simple saturation cycle, refrigerant is typically compressed to a superheated state, allowing for the possibility of recovering some heat from this gas by desuperheating it before it enters the condenser. The discharge temperatures in most refrigeration systems are quite high, generally ranging from 70°C to 100°C. This superheat can be utilized to heat water to approximately 60°C. The amount of heat recovered is usually around 10% to 15% of the total heat rejected by the condenser.

A heat recovery system is illustrated in fig 4. In a conventional system configuration, the discharge line from the compressor connects to a heat exchanger unit, commonly referred to as a desuperheater. The return line from the desuperheater is then connected to the condenser.

This setup facilitates the flow of high-temperature superheated refrigerant vapor from the compressor through the desuperheater and ultimately to the condenser. The desuperheater contains a circulating water system that absorbs thermal energy from the superheated refrigerant vapor. Heat transfer occurs due to the temperature difference between the hot refrigerant and the relatively cooler circulating water within the desuperheater.

Following attached is potential Recoverable Super Heat from Ammonia Refrigeration System:

Table 3: Recoverable superheat from Ammonia refrigeration systems [2]

Condensing Temperature (°C)	Estimated Discharge Temperature (°C)	Recoverable Heat (Kcal/hr)
43	114	1990
41	104	1800
38	99	1730
35	91	1525
32	86	1450

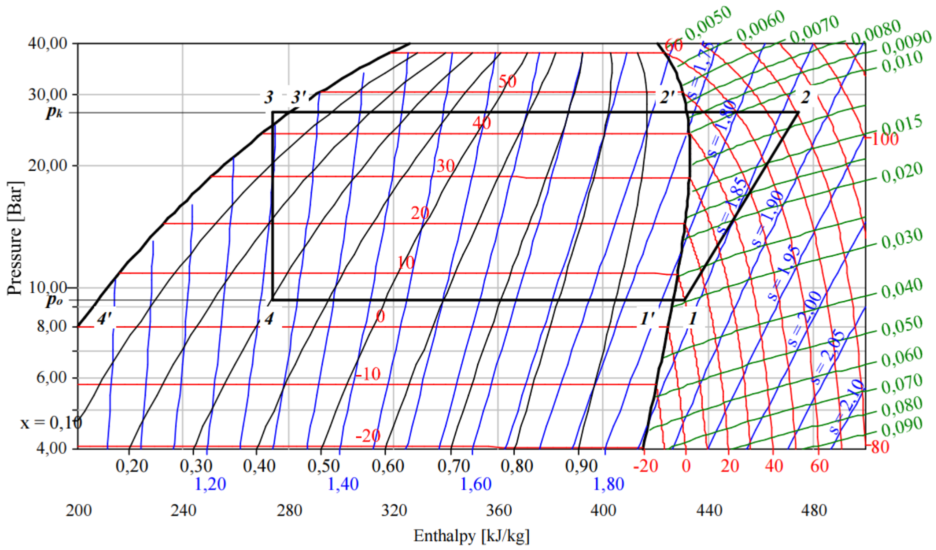

Figure 1: Typical single-stage refrigeration cycle [6]

Calculations : From the P-H chart in fig 1, the superheat value can be expressed as:

$$Q_P = \dot{m} \times (h_2 - h_2') \tag{5}$$

where:

- $\dot{m} = 8.4\,\mathrm{kg/s}$ is the mass flow rate of the refrigerant R134a in the refrigeration unit.
- h_2 and h_2' are the enthalpies of the refrigerant at specific operating points of the refrigeration unit (in kJ/kg).

For the refrigeration unit under consideration, the superheat value is calculated as follows:

$$Q_P = 8.4\,\mathrm{kg/s} \times (435\,\mathrm{kJ/kg} - 423\,\mathrm{kJ/kg}) = 100.8\,\mathrm{kW} \tag{6}$$

The total energy recovered in the system over one year amounts to:

$$\text{Total Energy} = 883,008\,\mathrm{kWh} \tag{7}$$

For the calculations of energy, environmental, and economic effects, it was assumed that the chilled water preparation and heat recovery system would operate at an annual average performance of approximately 85%. Additionally, the energy loss during the transfer to the heating node is estimated to be about 10%. Thus, the effective energy recovered can be calculated as:

$$\text{Effective Energy} = 883,008\,\text{kWh} \times 0.85 \times 0.90 = 675.50\,\text{MWh/year} = 2,431.80\,\text{GJ/year} \tag{8}$$

Consequently, the estimated energy savings amount to:

$$\text{Energy Savings} = 2,431.80\,\text{GJ/year} \times 31.08\,\text{PLN/GJ} = 75,580.30\,\text{PLN/year} \tag{9}$$

The estimation of costs related to adapting the system for heat recovery is provided in Table 4.

The simple payback time (SPBT) for the investment is calculated as follows:

$$\text{SPBT} = \frac{155,595.00\,\text{PLN}}{75,580.30\,\text{PLN/year}} = 2.06\,\text{years} \tag{10}$$

Table 4: Costs related to adapting the system to enable heat recovery [6]

No.	Item	Net value [EUR]	Gross value [PLN]
1	Heat recovery system with a tank	15,000.00	77,490.00
2	Additional costs of a control system	2,000.00	10,332.00
3	Labour and additional works	5,500.00	28,413.00
4	Additional transfer system to a heating node	9,371.00	39,360.00
Total:		**31,871.00**	**155,595.00**

Based on the analysis of active measures for improving building refrigeration systems, two key methods show promising results for energy efficiency. Free cooling, which utilizes low ambient temperatures to reduce compressor usage, demonstrates a significant 31.05% annual reduction in power consumption with a payback period of 1.81 years, saving 358,300.02 PLN annually. Similarly, waste superheat recovery, which captures and reuses heat from the refrigeration cycle, can recover approximately 675.50 MWh of energy annually with a payback period of 2.06 years, resulting in savings of 75,580.30 PLN per year. These findings suggest that both methods are economically viable solutions for improving the energy efficiency of building refrigeration systems.

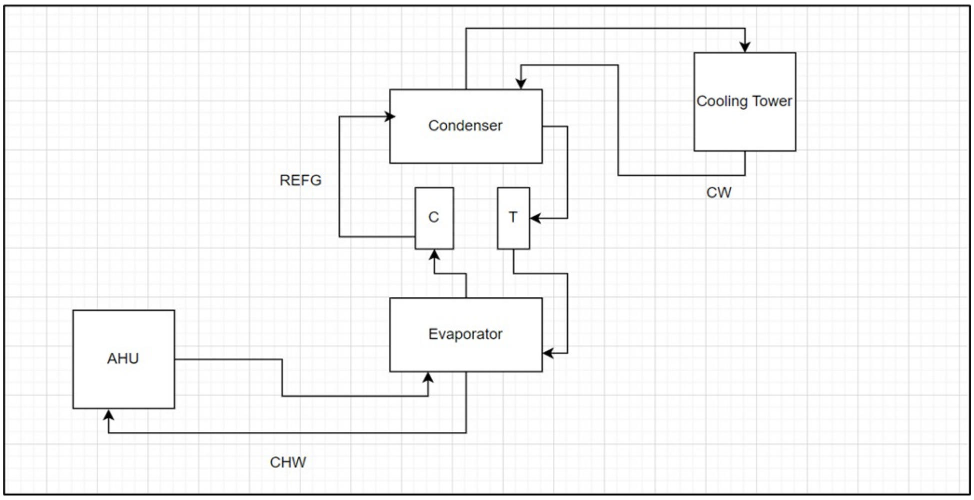

Figure 2: Traditional Chiller Working Plant

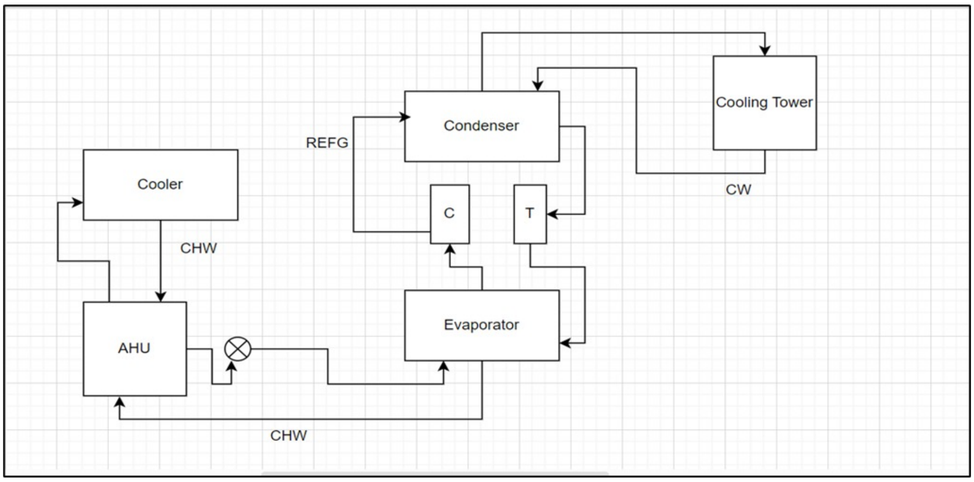

Figure 3: Free Cooling Process

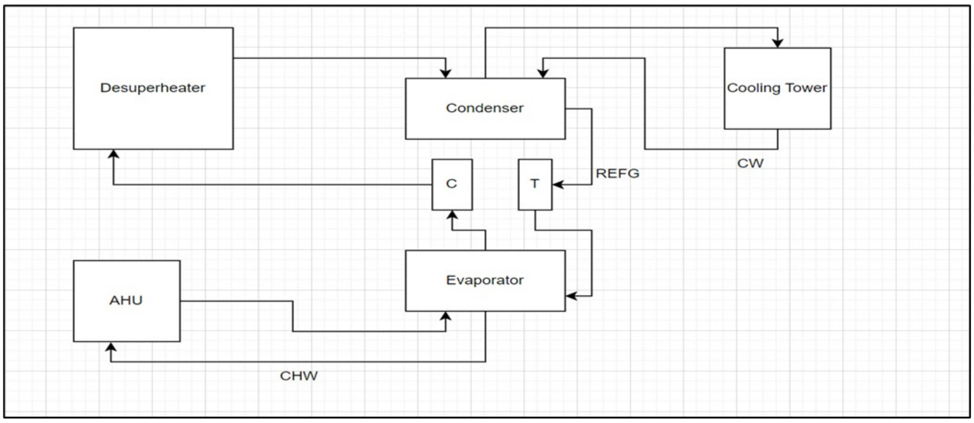

Figure 4: Heat Recovery System

5 Conclusion: Key Findings and Future Directions

5.1 Key Findings

We explored both passive and active strategies for enhancing energy efficiency in building systems, highlighting several important findings:

- **Passive House Principles:** An approach to passive house design emphasizes minimal heating energy requirements through effective insulation, airtight enclosures, heat recovery ventilation, and smart use of solar gains. The implementation of such principles can lead to a 90% reduction in annual energy consumption, as seen in the passive house case study in Germany [1].

- **Active Cooling Measures:** Free cooling provides an energy-efficient alternative for cooling in climates with sufficiently low ambient air temperatures. This method can significantly reduce the energy consumption of chillers, as depicted by the 35.2% reduction in compressor power in a 12-building complex [6].

- **Superheat Recovery:** reusing waste heat from refrigeration systems can significantly reduce energy consumption. Recovering superheat to preheat water and lower condenser loads can boost overall system efficiency by up to 15% emphasizing the potential of energy reclamation in modern HVAC systems.

5.2 Future Directions

As we move towards a more sustainable future, several areas of research and development could further enhance building energy efficiency:

- **Net-Zero Energy Buildings:** Moving beyond passive houses, the concept of net-zero energy buildings (NZEBs), which generate as much energy as they consume, will likely dominate future construction practices. Combining solar panels, wind energy, and advanced energy storage systems with passive house principles can push buildings towards self-sufficiency.

- **Scalable Retrofitting Solutions:** While new buildings can adopt energy-efficient designs from inception, retrofitting existing buildings presents a significant challenge. Research into cost-effective retrofit technologies, such as prefabricated insulation panels, smart HVAC systems, and heat recovery units, could help scale energy-saving measures across older building stock.

- **Sustainability and Materials:** The choice of construction materials plays a crucial role in the sustainability of buildings. Future research should explore the use of bio-based insulation materials, recyclable construction components, and low-carbon concrete, further reducing the environmental impact of both construction and energy consumption.

- **Policy and Incentives:** The role of government policies, building codes, and financial incentives will remain crucial in driving the adoption of energy-efficient practices. Future directions could involve carbon-neutral construction mandates, incentives for retrofitting projects, and subsidies for passive and NZEB constructions.

References

[1] J. Bere. *An Introduction to Passive House*. RIBA Publishing, 1st edition, 2019.

[2] Manor Enterprises. Energy savings by waste heat recovery from refrigeration and air conditioning systems: "how and how much", 2017. Brochure.

[3] W. Feist and J. Schnieders. Energy efficiency – a key to sustainable housing. *The European Physical Journal Special Topics*, 176(1):141–153, Sep 2009.

[4] Mariaenrica Frigione, Mariateresa Lettieri, and Antonella Sarcinella. Phase change materials for energy efficiency in buildings and their use in mortars. *Materials*, 12(8), 2019.

[5] Constantin Ionescu, Tudor Baracu, Gabriela-Elena Vlad, Horia Necula, and Adrian Badea. The historical evolution of the energy efficient buildings. *Renewable and Sustainable Energy Reviews*, 49:243–253, 2015.

[6] A. Rusowicz, A. Grzebielec, and A. Ruciński. Energy conservation in buildings using refrigeration units. In D. Čygas and T. Tollazzi, editors, *9th International Conference on Environmental Engineering*, page 6. Vilnius Gediminas Technical University Press Technika, 2014.

[7] United Nations Environment Programme. Global status report for buildings and construction: Beyond foundations: Mainstreaming sustainable solutions to cut emissions from the buildings sector, 2024.