Economizer Modes of Data Center Cooling Systems

White Paper 132

Revision 0

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> Executive summary

In certain climates, some cooling systems can save over 70% in annual cooling energy costs by operating in economizer mode, corresponding to over 15% reduction in annualized PUE. However, there are at least 17 different types of economizer modes with imprecise industry definitions making it difficult to compare, select, or specify them. This paper provides terminology and definitions for the various types of economizer modes and compares their performance against key data center attributes.

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Introduction

The rising costs of energy and the drive to be green are resulting in greater demand to conserve energy. The energy savings potential of operating in economizer mode in certain climates makes it attractive for use in IT environments. **Operating in economizer mode saves energy by utilizing outdoor air during colder months of the year allowing refrigerant-based cooling components like chillers and compressors to be shut off or operated at a reduced capacity.** Up until recently, operating in economizer mode was considered an option or a secondary mode of operation but is now becoming a requirement to meet efficiency targets set by data center operators and / or standards such as ANSI/ASHRAE Standard 90.1-2010, *Energy Standard for Buildings Except Low-Rise Residential Buildings*. Data center operators in some climates are finding that cooling systems can operate *primarily* in economizer mode allowing the refrigerant-based modes (i.e. mechanical cooling) to serve as the secondary mode of operation or backup.

Although the concept of economizer mode is recognized throughout the data center industry, little has been done to standardize the terminology and its definitions leading to confusion. A significant source of confusion lies in the use of the term "economizer" to describe a component within a cooling system or a subset of a cooling system. **An "economizer" is NOT an object; it IS a mode of operation.**

At the highest level, a cooling system can use air, water, or refrigerant to transport heat energy from inside the data center to the outdoors. The terms "air-side economizer" and "water-side economizer" are often used to describe cooling systems with an integrated economizer mode. Lacking other standard definitions, this paper proposes terminology and definitions for the various types of economizer modes that use air or water to transport heat energy to the outdoors. The operation of each type of economizer mode is described, with six types identified as the most beneficial for data centers. These six types of economizer modes are then compared across multiple attributes.

Link to resource
White Paper 59
The Different Types of Air Conditioning Equipment for IT Environments

This paper assumes the reader has a basic knowledge of the various types of heat rejection systems. For a better understanding of cooling components of various types of heat rejection systems see White Paper 59, *The Different Types of Air Conditioning Equipment for IT Environments*.

Purpose and function of economizer modes

There are many different devices and cooling technologies used to cool data centers. However, all of these systems use some or all of the following four basic elements:

- Heat transport: fans and / or pumps, moving fluid (such as air or water), that moves heat energy from the data center to the outdoor environment.
- Heat exchange: coils or vents that "hand-off" heat energy from one heat stream to the next. In all cases, there is a final heat exchange to the outdoor environment.
- Compressor: system that uses high and low pressure refrigerant, to force heat energy to flow "uphill" from a cold area (data center) to a hot area (outdoors in summer). The compressed high-pressure refrigerant is at a temperature much higher than the outdoor temperature. This "temperature boost" is what allows heat in the data center to flow to the outdoor environment.
- Evaporative assist: cooling towers, wetted filters, or sprays that evaporate water to facilitate the transfer of heat to the outdoor environment.

A typical water-cooled data center uses ALL of the above elements to cool the data center. The heat transport and compressor consume electrical energy in providing the cooling, and the evaporative assist consumes water.

> **> Free cooling**
>
> Economizer modes are sometimes referred to as "free cooling". While the term is useful to describe the general subject of economizer modes, it's important to note the following. An economizer mode partially or fully bypasses a compressor in a cooling plant. Most systems using economizer modes spend most of the time in a partial bypass mode, so part of the cooling energy is saved, but the cooling is not "free". Furthermore, even when an economizer mode operates in full bypass of the compressor, there is still significant energy used in transport of the heat via fans or pumps, and possibly in other functions such as humidification.* Even in this full economizer mode, the cooling is not "free".
>
> * In at least one design, the so-called "Yahoo chicken coop", heat transport takes advantage of natural convection using a special building design, in order to reduce or eliminate the need for heat transport fans.

The cooling system must be designed to work under the worst case conditions of full data center load and high outdoor temperature. At lower data center loads and cool outside temperatures, the system must do less work to cool the data center. Unfortunately, the various devices in the cooling plant are underutilized and not operating efficiently under these conditions. To increase efficiencies under these conditions, cooling devices have been improved to include variable speed drives, staging, and other functions. Nevertheless, they still require significant power. To help reduce the power used during the favorable conditions of light data center load and cool outdoor temperatures, economizer modes have been developed.

In an economizer mode, the compressor function is fully or partially bypassed, eliminating or reducing its energy use. The compressor is used to move heat from within the data center to the outdoor environment when the outdoor temperature is greater than the data center temperature. However, when the outdoor temperature is sufficiently below the data center temperature, the heat will naturally flow to the outside without the need of the "temperature boost" provided by the compressor, so its function is unnecessary. Therefore, under favorable conditions, the compressor can be bypassed, saving significant energy. Furthermore, for systems using evaporative assist, that function can also be shut down or bypassed if conditions are favorable, saving water.

Historically, building an economizer mode into a data center cooling system entailed extra cost and complexity, and was only justified in situations with extremely favorable weather conditions, such as high latitudes. However, this has changed and economizer modes are now considered advantageous in almost all locations for the following reasons:

- The operation of data center at partial loads increases the benefit of economizer modes, and more designers recognize that data centers spend a considerable fraction of their life at light load. The trend toward dynamic power variation of IT equipment will amplify this effect.
- The trend toward operation of data centers at higher IT air return temperatures has a dramatic effect on the percent of time economizer mode operation is possible, especially in warmer climates.
- Most new implementations of economizer modes can now operate in a "partial" economizer mode, which greatly increases the amount of energy saved in almost all cases.
- The tools available for quantifying the energy saved by implementing economizer modes are now improved and frequently predict significant savings possibilities with excellent ROI.
- Real-world experience with economizer modes and improvement of controls and monitoring systems, have increased confidence that these modes do not adversely affect the reliability of data centers.

It is this concept of a bypass of the compressor function that is central to all economizer modes. How this bypass is accomplished (and the benefits obtained) depend on the design of the cooling plant, as explained in the following sections.

Types of economizer modes

There are 19 fundamental types of economizer modes, and of these, 15 can realistically be used in a production data center (all six types that use air and nine types that use water). The other four types that use water were not considered because they bring condenser water directly into the data center which increases fouling in equipment. **Figure 1** logically organizes these 15 types of economizer modes[1]. Each type is described further in the following sections. The modes highlighted in yellow are analyzed later in this paper.

[1] CRAH – computer room air handler, CRAC – computer room air conditioner

> Series / Parallel

Economizer modes can be designed and configured in one of two ways; series or parallel.

In a series configuration, the component that bypasses the compressor (e.g. plate-and-frame heat exchanger) is installed in series with the compressor. This configuration allows for partial economizer mode where the heat exchanger "pre-cools" the air or water. This reduces the total heat energy that the compressor must reject, saving a significant amount of energy.

In a parallel configuration, the component that bypasses the heat pump is installed in parallel with the heat pump. This configuration prevents the ability to operate in partial economizer mode. This "all or nothing" approach fails to capitalize on the significant energy savings available by operating in partial economizer mode.

To fairly compare different economizer modes, it is important to include all of the necessary cooling system components required to operate in that mode. For example, sometimes the plate-and-frame heat exchanger in a water-cooled chiller plant is mistaken as "*the*" economizer, when in fact it is only one component that allows the cooling system to operate in economizer mode. In this case, the cooling tower, condenser pumps, chilled water pumps, and computer room air handlers (CRAH) are all **required** in order to operate in economizer mode. It is impossible to operate in economizer mode with any one of these devices missing, even on the coldest day. This is why, in general, it is wrong to refer to an "economizer" in a data center and more accurate to refer to "economizer modes" of operation of the cooling system.

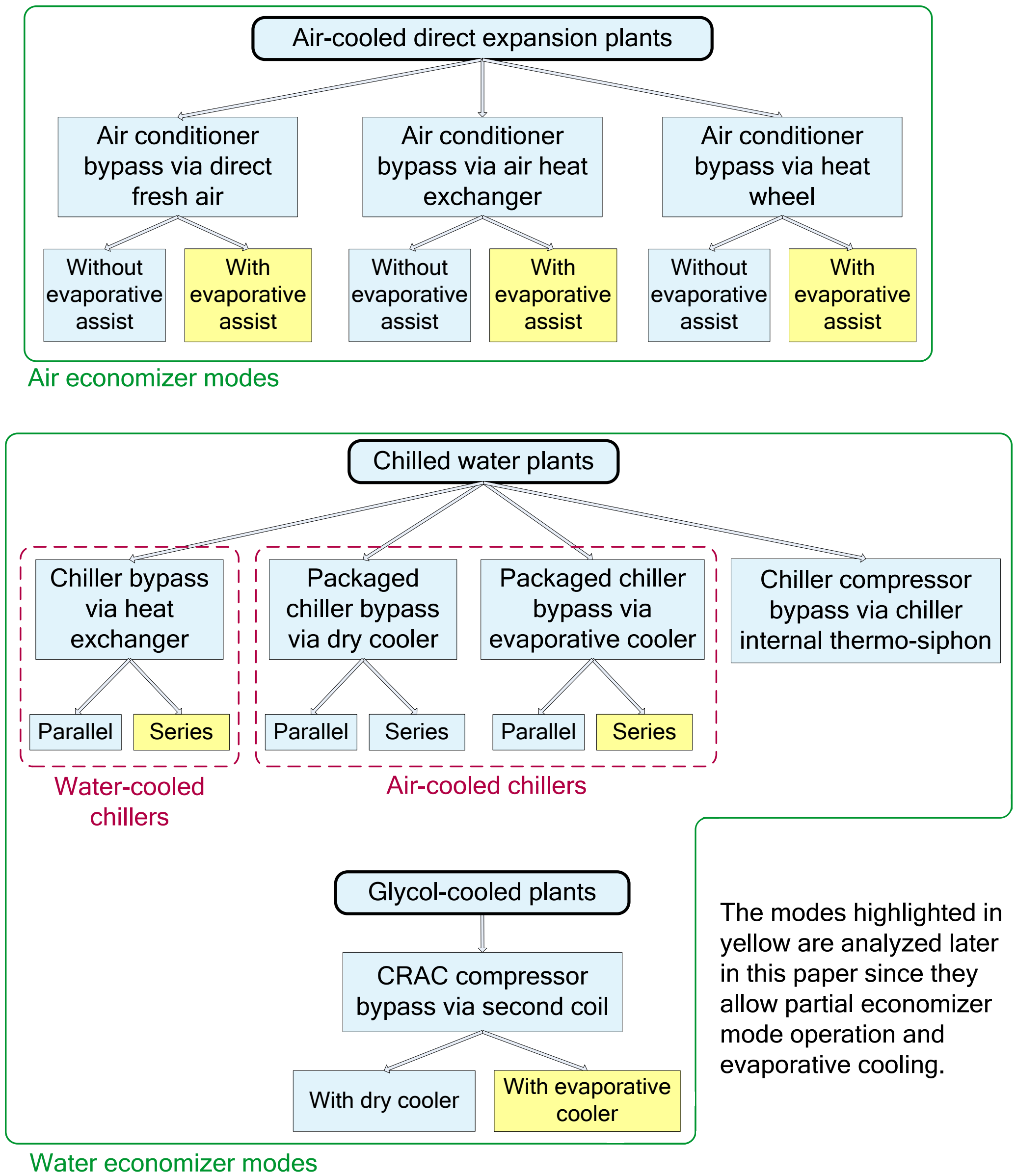


Figure 1

Types of economizer modes

The following sections describe each type of economizer mode. Each section begins with a list of all the necessary components for operation in economizer mode (i.e. completely unassisted by mechanical vapor compression). All descriptions assume that a control system[2] is required.

Air conditioner bypass via direct fresh air

Key components: fans, louvers, dampers, filters, (wetted media pads and pump – when used with evaporative assist)

A fresh air economizer mode (sometimes referred to as direct air) uses fans and louvers to draw a certain amount of cold outside air through filters and then *directly* into the data center when the outside air conditions are within specified set points, as shown in **Figure 2**. Louvers and dampers also control the amount of hot exhaust air that is exhausted to the outdoors and mixed back into the data center supply air to maintain environmental set points. Although supply air is filtered, this does not completely eliminate fine particulates such as smoke and chemical gases from entering the data center.

This type of economizer mode can also be used with **evaporative assist** whereby the outside air also passes through a wet mesh material before entering the data center. In dry geographic locations, evaporative assist can lower the air temperature by up to 19°C (35°F), which results in additional economizer mode hours. This is the same cooling effect someone experiences when they step out of the ocean and into an ocean breeze. Note that using evaporative assist with this type of economizer mode increases the data center humidity because the fresh air brought directly into the data center is passed over the evaporative medium. Evaporative assist is most beneficial in dry climates. For more humid climates, evaporative assist should be evaluated based on ROI (return on investment). This type of economizer mode allows for partial economizer mode operation.

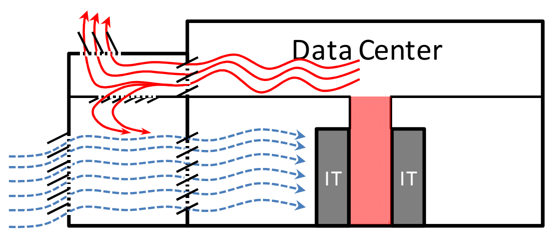


Figure 2

Air conditioner bypass via direct fresh air mode

Air conditioner bypass via air heat exchanger

Key components: fans, air-to-air fixed plate heat exchanger, (wetted media pads, pump – when used with evaporative assist)

An air conditioner bypass via air heat exchanger mode (sometimes referred to as indirect air) uses outdoor air to *indirectly* cool data center air when the outside air conditions are within specified set points. This mode uses fans to blow cold outside air over a series of plates or tubes which in turn cool the hot data center air on the other side of the plates or tubes completely isolating the data center air from the outside air (see **Figure 3a**). This type of economizer mode can also be used with **evaporative assist** whereby the outside of the plates or tubes are sprayed with water which further lowers the temperature of the outside air and thus the hot data center air. Unlike the previous economizer mode, the evaporative assist in this case does not increase the humidity within the data center. **Figure 3b** provides an illustration of an air-to-air heat exchanger with evaporative assist and an example of a complete cooling system with this type of economizer mode. This type allows for both full and partial economizer modes.

[2] Control system refers to the components that regulate the operation of a system such as closing a water valve or air louver upon reaching a certain outdoor temperature.

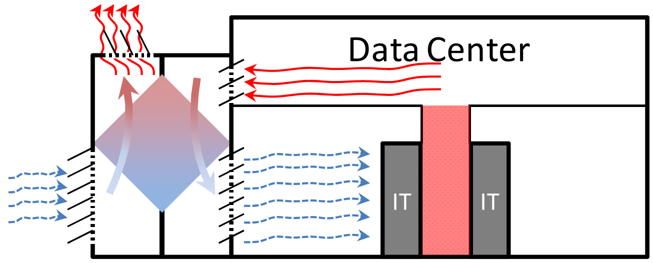


Figure 3a

Air conditioner bypass via air heat exchanger mode

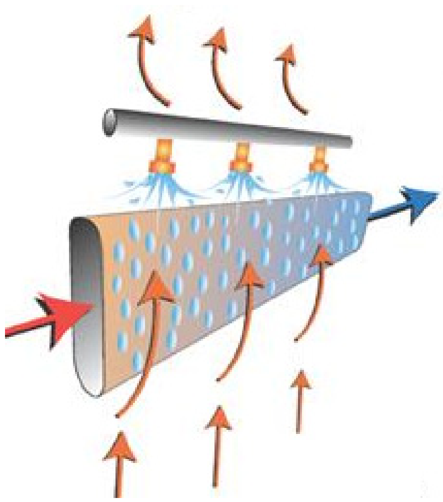


Figure 3b

Illustration of an air-to-air heat exchanger with evaporative assist (left) and an example of a complete cooling system with an integrated air conditioner bypass via air heat exchanger mode (right)

Air conditioner bypass via heat wheel

Key components: fans, heat wheel, (wetted media pads and pump – when used with evaporative assist)

An air conditioner bypass via heat wheel mode uses fans to blow the cold outside air through a rotating heat exchanger which preserves the dryer air conditions of the data center space as shown in **Figure 4** along with an example of a heat wheel. Heat wheels depend on a special material that does not allow contaminates to pollute the data center air. This type of economizer mode can also be used with **evaporative assist** whereby the outside air is further cooled by moving through a wet mesh material. This type allows for both full and partial economizer modes.

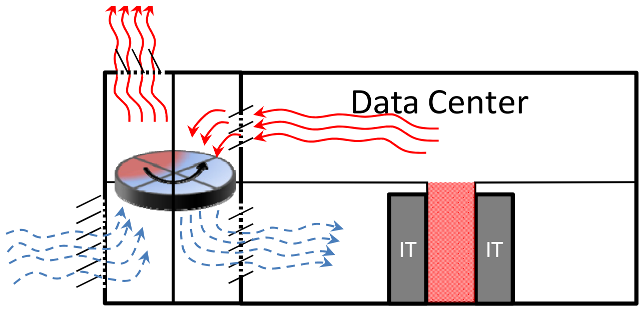


Figure 4

Air conditioner bypass via heat wheel mode (left) and example of a heat wheel (right)

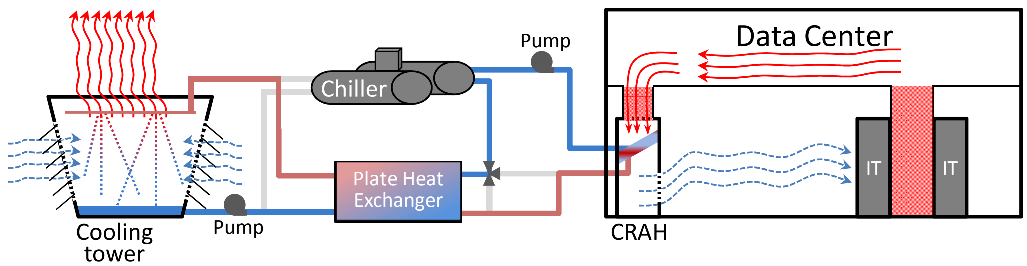
Chiller bypass via heat exchanger

Key components: cooling tower, pumps, valves, plate-and-frame heat exchanger, CRAH

A chiller bypass via heat exchanger economizer mode uses the condenser water to *indirectly* cool the data center chilled water when the outside air conditions are within specified set points. Pumps move the condenser water through a plate-and-frame heat exchanger to cool the chilled water used in CRAHs without mixing the two water streams as shown in **Figure 5**. Valves bypass the chiller allowing it to turn off depending on how cold the condenser water is. This economizer mode allows for partial operation when the heat exchanger is in series with the chiller. Although not discussed in this paper, this type of economizer mode may also use a large body of water (e.g. lake) as a source of cold water.

Figure 5

Chiller bypass via heat exchanger mode



Chiller compressor bypass via chiller internal thermo-siphon

Key components: cooling tower or dry cooler, chiller with thermo-siphon, pumps, valves, CRAH

Some chillers offer a thermo-siphon economizer mode option that allows the compressor to be turned off when the outside air conditions are within specified set points. In this mode, the chiller acts like a simple heat exchanger. The principle of thermo-siphon causes the hot refrigerant to naturally move toward the cold condenser coil where is it cooled. The cold refrigerant then relies on gravity or a pump to travel back to the evaporator coil where it cools the data center chilled water. The refrigerant becomes hot again and the cycle repeats. The thermo-siphon feature eliminates the need for the plate-and-frame heat exchanger in the previous type of economizer mode. However, this economizer mode does not allow the chiller to operate in partial economizer mode because the compressor must remain off when running in thermo-siphon mode.

Packaged chiller bypass via dry cooler (or via evaporative cooler)

Key components: dry cooler, pumps, valves, CRAH (wetted media pads, pump – when used with evaporative cooler)

A packaged chiller bypass via dry cooler economizer mode uses a heat exchanger known as a dry cooler to *directly* cool the data center chilled water when the outside air conditions are within specified set points. Pumps move the chilled water (usually a glycol mix) through a dry cooler where the cold outside air cools the chilled water that supplies the CRAHs as shown in **Figure 6a**. Valves bypass the chiller allowing it to turn off or operate more efficiently depending on how cold the outside air is. Partial economizer mode operation is only possible when the heat exchanger is in series with the chiller. Note that the dry cooler and controls in **Figure 6a** are fully integrated into the packaged chiller solution. **This is the assumed solution for this economizer mode type.** This type of solution has a smaller footprint and provides significantly more predictable and efficient economizer mode operation compared to field-assembly of the same components. An example of a packaged chiller solution with this type of economizer mode is shown in **Figure 6b**.

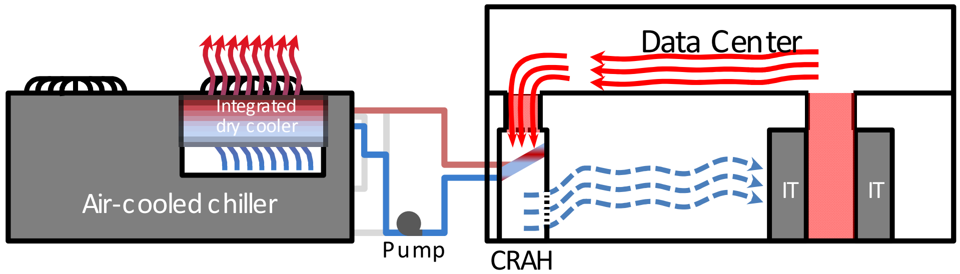


Figure 6a

Packaged chiller bypass via dry cooler mode

Figure 6b

Example of a packaged chiller with integrated dry cooler

This type of economizer mode can also be used with **evaporative assist** whereby the outside air is further cooled by moving through a wet mesh material or an atomized water spray which further reduces the chilled water temperature and increases the number of hours operating in economizer mode. This requires that the dry cooler be replaced with an evaporative cooler.

CRAC compressor bypass via second coil

Key components: dry cooler, pumps, CRAC with second coil (wetted media pads, pump – when used with evaporative cooler)

In this type of economizer mode, the direct expansion (DX) CRAC includes an independent second coil that uses the condenser water during economizer mode operation. When the outside air conditions are within specified set points, pumps move the condenser water through the dry cooler where the cold outside air cools the condenser water that supplies the second coil in the CRAC (**Figure 7**). This economizer mode allows for partial operation and can use **evaporative assist**. This requires that the dry cooler be replaced with an evaporative cooler. Note that a cooling tower could also be used to cool the condenser water but increases water treatment requirements therefore it was not considered for data center use.

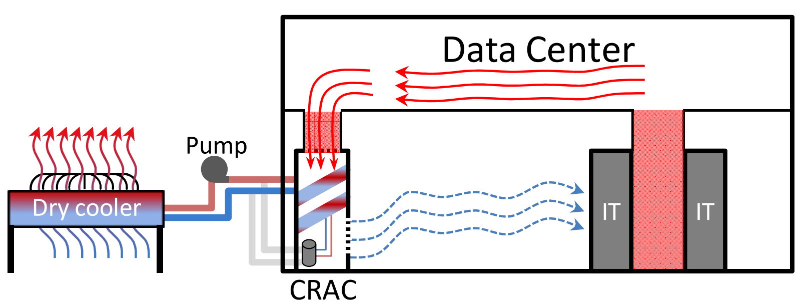


Figure 7

CRAC compressor bypass via second coil mode

Comparison of the different economizer modes

An economizer mode must take advantage of a wide range of outdoor conditions in order to maximize the number of economizer mode hours and save energy. **However, in periods of extreme hot outdoor conditions, it is necessary to at least partially depend on a refrigerant-based mode (i.e. mechanical cooling) to reliably maintain data center environmental conditions while saving energy. There are two key economizer mode attributes that help with this:**

1. Partial economizer mode operation whereby compressor operates at a reduced load
2. Evaporative assist

A high level assessment of each of the 15 types of economizer modes shown in **Figure 1** concludes that six of the 15 types employ both of these attributes. **Table 1** compares these six types of economizer modes against various qualitative attributes described below. The blue shading depicts the best type of economizer mode for the specific attribute. **Table 2** compares these six types of economizer modes against various quantitative attributes.

Table 1

Qualitative comparison between types of economizer modes (blue cells indicate best performer for that attribute)

Economizer mode attribute	Air economizer modes: Air conditioner bypass via direct fresh air (w/ evap assist)	Air economizer modes: Air conditioner bypass via air heat exchanger (w/ evap assist)	Air economizer modes: Air conditioner bypass via air heat wheel (w/ evap assist)	Water economizer modes: Chiller bypass via heat exchanger [3]	Water economizer modes: Packaged chiller bypass via evaporative cooler [3]	Water economizer modes: CRAC compressor bypass via second coil (w/ evap assist)
Building shell compatibility	May require building shell modification	May require building shell modification	May require building shell modification	No issue with building shell	No issue with building shell	No issue with building shell
Ability to retrofit	Not logical to retrofit into existing system	Not logical to retrofit into existing system	Not logical to retrofit into existing system	Practical if space available	Practical if space available	Requires swapping out CRAC unit
Complexity of controls	Fewer devices to control	Fewer devices to control	Fewer devices to control	Most devices to control	Moderate number devices to control	Moderate number devices to control
Data center humidity control	Dependent on outdoor humidity	Independent of outdoor humidity	Independent of outdoor humidity	Independent of outdoor humidity	Independent of outdoor humidity	Independent of outdoor humidity
Life expectancy	20-40 years on heat exchanger	20-40 years on heat exchanger	20-40 years on heat exchanger	10-15 yrs on plate heat exchanger	10-20 years on evaporative cooler	10-20 years on cooling unit
Availability risks -loss of cooling water - poor air quality - fire suppression	Highly susceptible to outdoor air quality Shutdown required with clean agent suppression	Low downtime risk due to water loss. No risk due to poor air quality, or fire suppression	Low downtime risk due to water loss. No risk due to poor air quality, or fire suppression	Downtime due to loss of make-up water for cooling tower	No downtime due to water loss, poor air quality, or fire suppression	No downtime due to water loss, poor air quality, or fire suppression
Footprint	0.41 ft^2 / kW 0.038 m^2 / kW	0.788 ft^2 / kW 0.073 m^2 / kW	1.72 ft^2 / kW 0.16 m^2 / kW	1.94 ft^2 / kW 0.18 m^2 / kW	3.34 ft^2 / kW 0.31 m^2 / kW	2.02 ft^2 / kW 0.19 m^2 / kW
Need for backup refrigerant mode	Fully sized backup in case of poor outdoor air quality	Partially sized for extreme climates	Partially sized for extreme climates	Partially sized for extreme climates	Partially sized for extreme climates	Partially sized for extreme climates

[3] Assumes heat exchanger is in series with the chiller which allows for partial economizer operation.

Building shell compatibility

Air conditioner bypass via direct fresh air, via air heat exchanger, and via air heat wheel all require air ductwork from the outdoor cooling equipment to the data center IT room. In general this requires that the building be specifically designed with space for this ductwork, or designed such that the IT room directly abuts an outdoor location suitable for the cooling equipment. Therefore, these types of economizer modes are often difficult to install in existing building shells and multi-story buildings. Economizer modes that use pipes are more flexible in their installation options because water piping transfers heat in a much smaller physical space that can be accommodated in existing chase ways.

Ability to retrofit

The typical goal in a retrofit application is to re-use as much of the existing cooling infrastructure as possible. It is practically impossible to retrofit a traditional cooling system with an air conditioner bypass via direct fresh air economizer mode since the existing cooling infrastructure is incompatible (the traditional system uses water while the other uses air). In a typical data center using CRAH or CRAC units, there are basically three ways to retrofit an economizer mode while re-using existing equipment.

“The control system for standardized pre-engineered cooling systems with integrated economizer mode is developed in conjunction with the hardware. This makes the control system inherently more reliable than customized control systems developed for unique cooling system installations in the field.”

The first and most common way is to add a heat exchanger that bypasses a water-cooled chiller (i.e. Chiller bypass via heat exchanger economizer mode). This typically requires the installation of a plate-and-frame heat exchanger near the chiller, with associated controls and bypass valves. The heat exchanger is much smaller than a chiller, so there is often sufficient room for the heat exchanger in the existing chiller room.

The second way is to add a heat exchanger that bypasses an air-cooled chiller (i.e. Packaged chiller bypass via evaporative cooler economizer mode). This typically requires the installation of an evaporative cooler near the chiller, with associated controls and bypass valves. The total evaporative cooler footprint may be much larger than the chiller depending on the climate, so sufficient space is required.

The third way is to add a heat exchanger that bypasses the compressor in a glycol-cooled DX system (i.e. CRAC compressor bypass via second coil economizer mode). This is much more difficult and impractical to do since the second coil must be placed inside the cooling unit cabinet. Retrofitting this type of cooling system realistically requires the replacement of the entire CRAC unit with one that includes a second coil.

Complexity of controls

The transition between economizer mode and refrigerant-based mode can be very complicated and could result in a temporary loss of cooling during the transition. Ultimately, the reliability of this transition rests on the controls. **The control system for standardized pre-engineered cooling systems with integrated economizer mode is developed in conjunction with the hardware. This makes the control system inherently more reliable than customized control systems developed for unique cooling system installations in the field.**

Air conditioner bypass via air heat exchanger or via heat wheel economizer modes have the simplest control systems. The most complex economizer mode control system is the chiller bypass via heat exchanger due to the deadband between the low condenser water temperature required by the plate-and-frame heat exchanger and the higher condenser water temperature required by the chiller.

> **Regulations and economizer modes**
>
> Economizer modes have typically been considered an option in a data center design. The customer could decide if they wanted to include economizer mode capabilities, based on their own view of the costs and benefits. However, there is a trend to regulate minimum performance requirements for new data centers, and these requirements may explicitly or implicitly require the implementation of economizer modes.
>
> The cornerstone regulation affecting this issue is ANSI/ASHRAE Standard 90.1-2010 "Energy Standard for Buildings Except Low-Rise Residential Buildings". This standard specifies minimum performance requirements for energy performance for buildings, and has recently been expanded to include data centers. While ASHRAE is not a legal body that enforces standards, many regulatory authorities, including the US Government and local building codes, have adopted this standard. Furthermore, organizations that set forth requirements for green buildings, like the LEED standard from the US Green Building Council, have adopted ASHRAE 90.1 as a minimum baseline for energy performance.
>
> For most data centers that follow ASHRAE guidelines, ASHRAE 90.1 defines a baseline data center cooling system that is used to establish the minimum performance requirement. This baseline is a typical chilled water system with the "chiller bypass via fluid heat exchanger" economizer mode as described earlier in this paper. While 90.1 does not prescribe that this exact system be used, whatever system is used in a data center must meet or exceed the performance of this baseline system, which includes an economizer mode. This suggests that **almost every new data center must have some kind of economizer mode**.

Data center humidity control

All but one type of economizer mode in **Table 1** isolates the outdoor air from the air inside the data center. The data center humidity is therefore unaffected by the economizer mode even when the outdoor humidity level is high. However, the air conditioner bypass via direct fresh air economizer mode supplies outdoor air directly into the data center which drastically reduces the number of hours in economizer mode in humid climates. While it's possible to control the humidity, the extra energy used may offset the energy savings from economizer mode.

Life expectancy

Cooling systems that use water to transport heat energy generally have a shorter life expectancy than those that use air. This is due to the fouling effects of water flowing through piping. The limiting factor for cooling systems that use evaporative assist tends to be the surfaces subjected to the water. Overall, the life expectancy of any cooling is significantly affected by the amount of maintenance performed over its life.

Availability risks

All types of economizer modes are susceptible to external threats such as hurricanes, tornados, and earthquakes. However, there are more common threats that must be considered.

- **Loss of cooling water** – loss of municipal water supply can occur due to construction projects in the vicinity of a data center, whether through planned or unplanned outages. Since water-cooled chillers typically rely entirely on cooling towers that operate continuously, the chiller bypass via heat exchanger economizer mode is most susceptible. This threat is usually addressed by installing a water storage tank large enough to sustain an outage for 24 hours or more. A loss of cooling threat to the evaporative assist stage of the other types of economizer modes is much less likely because it must coincide with hot, dry outdoor conditions.

  Systems that also rely on evaporative assist as a means of providing cooling throughout the entire year are also susceptible to a loss of cooling water. This can be addressed by installing water back-up as described above or sizing the mechanical cooling system to handle 100% of the load.

- **Poor air quality** – economizer modes that supply outdoor air directly into the data center may pose a threat to IT equipment. Some of the air filters on these cooling systems are effective in filtering out particles in micron range such as small as microorganisms. However, under the threat of volcanic ash, smoke from a nearby fire, or sand storm, fresh air economizer modes may need to switch to refrigerant cooling since the filters would quickly become clogged. This threat is usually addressed by installing a redundant chiller plant capable of supporting the heat load for the entire data center. In economizer modes that use wetted media for evaporative assist, the pads are susceptible to particulate buildup. In these cases, the pads will most likely require replacement after this threat.

  ASHRAE has a white paper and a book on the subject of *Particulate and Gaseous Contamination in Datacom Environments*. Both publications provide detail on the modes of failures that can be caused by gaseous and particulate contamination, particularly in direct fresh air economizer mode applications located in industrial areas. The publication also provides guidelines for allowable substances and operating conditions to ensure trouble free operation.

- **Fire suppression inside data center** – data centers that depend on clean agent fire suppression systems (i.e. FM200, INERGEN, ECARO-25) must seal the data center space in order to maintain the proper concentration of clean agent to effectively suppress a fire. This requires closing all air dampers and doors which is problematic for economizer modes that supply fresh air directly into the data center. As with a poor air quality threat, this threat is addressed by ensuring the mechanical system is capable of handling 100% of the data center heat load.

Footprint

The footprint of the different cooling systems accounts for space for all components including those required for economizer mode and the cooling units in the data center. The footprint is normalized to the rated data center capacity (i.e. the maximum IT load the data center can support). The air conditioner bypass via direct fresh air cooling system has the smallest footprint. The air conditioner bypass via air heat exchanger cooling system footprint is only slightly higher due to the addition of an air-to-air heat exchanger. The air conditioner bypass via air heat wheel cooling system has the largest footprint of all the “air-based” economizer modes” and is nearly as large as a chilled water plant with cooling tower.

Requirement for backup refrigerant mode

While it is possible for a cooling system to forgo a refrigerant-based cooling mode and depend entirely on an economizer mode, it increases the risk of downtime and is not recommended for high availability production data centers. Furthermore, very few locations around the world provide a cold climate year-round. And of those that do, even fewer have the necessary accessibility, fiber optic lines, labor pool, and other resources required to operate a data center. Therefore, in most cases, an economizer mode will need at least a partially rated refrigerant-based backup mode to assist on the hottest days of the year. The more “heat exchange handoffs” that take place in an economizer mode, the more likely it is that a fully rated refrigerant-based mode is required.

For example, a data center with a chiller bypass via heat exchanger economizer mode exchanges heat energy at three points: at the CRAH, at the plate-and-frame heat exchanger, and at the cooling tower. **For this data center to provide 20°C (68°F) air to servers at 100% economizer mode operation, the maximum outdoor wet bulb temperature must be about 2°C (35°F) or lower year round[4].** If the chiller is de-rated to 50% of the design capacity, the maximum outdoor wet bulb temperature must be about 7°C (45°F) or lower year round, which is still too low for a practical data center location. This is why this type of economizer mode requires a fully rated chiller for a backup mechanical system.

Air conditioner bypass via direct fresh air economizer mode does not have any heat exchanges since the outdoor air is supplied directly into the data center. This means it can operate all year, in dryer climates, with a partially rated mechanical cooling system. However, due to the air quality risk discussed above, and the need for humidity control, a fully rated mechanical system is required. Although the air conditioner bypass via air heat exchanger economizer mode has one “heat exchange”, it avoids the air quality risk and humidity control issues and thus the capital and operational expense of a fully rated mechanical system.

In a future where virtual machines allow critical processes to fail over to other data centers, it is realistic to expect some data centers to operate entirely on economizer mode with no refrigerant backup at all. IT equipment inlet temperature thresholds are expected to increase in the future making full-time economizer mode operation even more probable.

[4] Assumes data center is 100% loaded with hot aisle containment, 14°C (57°F) chilled water supply

Table 2

Quantitative comparison between types of economizer modes

Economizer mode attribute	Air economizer modes			Water economizer modes		
	Air conditioner bypass via direct fresh air (w/ evap assist)	Air conditioner bypass via air heat exchanger (w/ evap assist)	Air conditioner bypass via air heat wheel (w/ evap assist)	Chiller bypass via heat exchanger [5]	Packaged chiller bypass via evaporative cooler [5]	CRAC compressor bypass via second coil (w/ evap assist)
The following attributes are based on a 1MW data center at 50% IT load, located in St. Louis, MO, U.S. See side bar for all assumptions.						
Annual water consumption	100 gal 379 L	1,262,000 gal 4,777,000 L	257,000 gal 973,000 L	7,000,000 gal 26,000,000 L [6]	128,000 gal 485,000 L	128,000 gal 485,000 L
Capital cost of entire cooling system	$2.2 / watt	$2.4 / watt	$2.8 / watt	$3.0 / watt	$2.3/ watt	$2.0 / watt
Annual maintenance cost of entire system [7]	75%	75%	83%	100%	100%	92%
Total cooling energy	737,506	340,365	377,625	589,221	736,954	960,974
Annual hours - full economizer mode	5,723	7,074	5,990	4,705	5,301	4,918
Annual hours - partial economizer mode	0	1,686	2,770	3,604	1,773	3,800
Est. annual PUE	1.34	1.25	1.26	1.31	1.34	1.39

Annual water consumption

Economizer modes used with cooling towers are subject to the most water consumption compared to some other types of economizer modes due to the evaporation of water in the cooling tower. This is because the evaporation process occurs continuously year round. Cooling towers consume approximately 40 gallons per minute / 1,000 tons of cooling capacity (151.4 liters per minute)[8]. The evaporative assist component of the other economizer modes consumes water to a much lesser extent since it only uses the evaporative assist process during the hotter periods of the year.

> Economics of evaporative assist

The cost of evaporative coolers and evaporative assist in general include the material cost, water usage, and water treatment. These costs must be considered when deciding upon a data center cooling system.

Evaporative assist is most effective in dry climates such as Las Vegas and Dubai. The cost of an evaporative cooler must be balanced against its effectiveness in climates that are more humid. It is possible to spend more on evaporative cooling than is saved on cooling system energy.

Capital cost of entire cooling system

Capital cost includes all the materials, installation labor, design costs, and all project fees associated with the entire cooling system in terms of dollars per watt of IT load. For example, in a “chiller bypass via heat exchanger” economizer mode, the chiller is also included in the capital cost. In fact, this cooling system has the highest capital cost of all the other systems due to the added cost of the cooling tower, piping, pumps, and custom control system. The design and implementation for such a control system represents a significant cost because most if not all of the individual components are sourced from different vendors which requires custom coding, testing, verification, and tuning to ensure the entire cooling system is reliable and realizes the expected savings. The cost of “tuning” this system is likely to span a year or

[5] Assumes heat exchanger is in series with the chiller which allows for partial economizer operation.

[6] Total cooling tower water consumption estimated from evaporation, drift, and blowdown http://www.cheresources.com/ctowerszz.shtml (scroll down page) - accessed July 23, 2010

[7] Maintenance cost is shown as percent of a baseline traditional chiller / tower cooling system

[8] Arthur A. Bell, Jr., *HVAC Equations, Data, and Rules of Thumb* (New York: McGraw-Hill, 2000), p. 243

> **> Table 2 assumptions**
>
> Data center capacity: 1,000 kW (no redundancy)
>
> Location: St. Louis, Missouri, USA
>
> Total IT load: 500 kW
>
> Row-oriented cooling (water economizer modes)
>
> Dropped ceiling (air economizer modes)
>
> Hot air containment (all modes)
>
> Variable speed CRAH fans
>
> Average temperature delta across servers: 13.9°C / 25°F
>
> Average rack inlet temperature: 24°C / 75°F
>
> Maximum server inlet air at 55% relative humidity
>
> Maximum dew point: 10°C / 60°F
>
> Ratio of cooler to IT airflow: 120%
>
> Design chilled water delta-T: 6.7°C / 12°F
>
> Chiller COP * IPLV: 9
>
> Minimum tower water temperature: 4.4°C / 40°F limited by basin heater to prevent freezing
>
> Cooling tower design range: 5.6°C / 10°F

more. This analysis treated these costs as a capital expense but they may also be considered an operational expense. The cooling system with the packaged chiller bypass via evaporative cooler economizer mode costs approximately 23% less since it does not require the stated heat rejection components and degree of tuning. However, the overall data center PUE is worse due to this system's lower efficiency.

Annual maintenance cost of entire cooling system

The chiller / cooling tower system is a very common cooling system used in data centers and serves as a good benchmark for other cooling system maintenance costs. Therefore, the annual maintenance costs are shown in **Table 2** as percent of a chiller / tower cooling system. Annual maintenance includes maintenance for all the components of the cooling system for all modes of operation including economizer mode. For example, in a chiller bypass via heat exchanger economizer mode, the chiller is also included in the maintenance cost. The cooling systems with "air-based" economizer modes have a lower maintenance cost than the other economizer modes which have a higher component count and are more complex.

Total cooling energy

This is the total annual energy consumed by the entire cooling system. The economizer mode with the largest energy cost is the CRAC compressor bypass via second coil. This is due mainly to the energy penalty of having distributed cooling systems. The economizer mode with the lowest energy consumption is the air conditioner bypass via air heat exchanger. The air conditioner bypass via air heat wheel consumes only slightly more energy.

It is also helpful to benchmark the economizer mode energy consumption to a traditional chilled water / cooling tower system since the majority of data centers 1MW and lager use this. The baseline system assumes perimeter cooling without containment, no economizer mode, 7.2°C (45°F) chilled water supply temperature[9], and constant speed CRAH fans. Using this benchmark, **Figure 8** compares the cooling load factors (CLF)[10] of the economizer mode types against the benchmark chilled water plant across 11 cities where large data centers are commonly located. CLF is the portion of the PUE dedicated to a data center's cooling system.

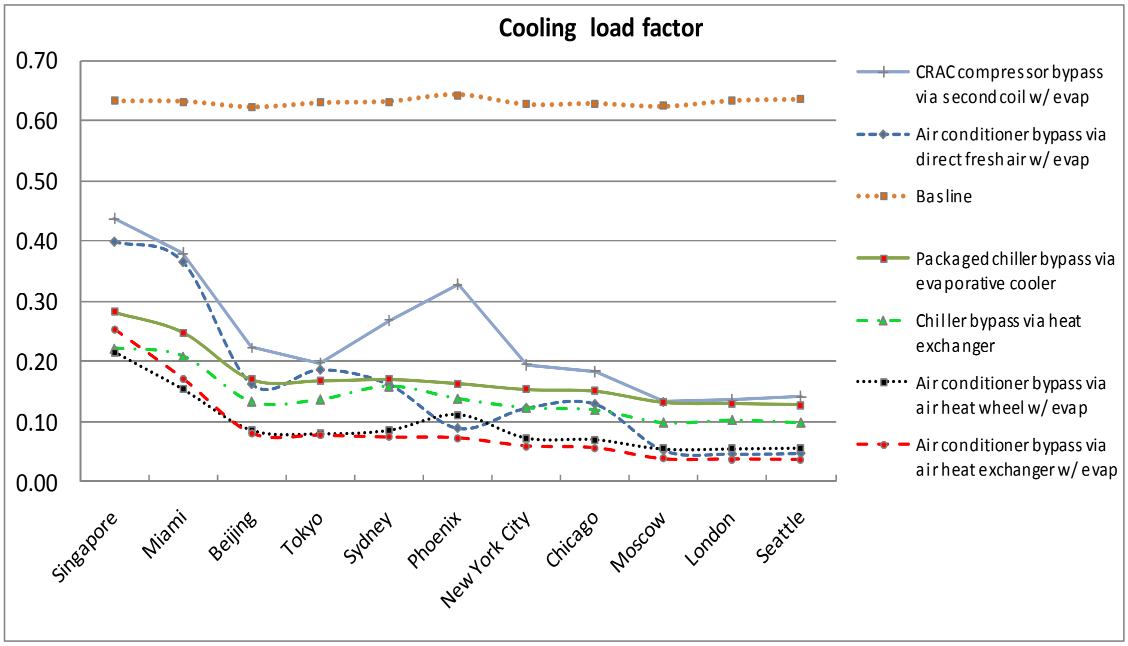
All the economizer modes provided cooling energy savings over the baseline cooling system. The air conditioner bypass via air heat exchanger mode provides the lowest cooling energy consumption in nearly all climates with an average of 381,385 kWhrs. **This represents a 86% cooling system energy savings when compared to the average baseline cooling energy consumption of 2,761,262 kWhrs.** The air conditioner bypass via air heat wheel mode also performs well.

[9] For economizer modes that use chilled water, the chilled water supply temperature should be higher than typical chilled water plants. Setting the chilled water supply temperature to 10-15°C (50-59°F) significantly increases the number of economizer mode hours.

[10] Cooling Load Factor (CLF) is the total energy consumed by the cooling system divided by the IT Load energy. IT load energy used in this analysis was 500kW x 8760 hours/year. For more information on (CLF) see page 7 of The Green Grid white paper #1 - accessed December 21, 2010 http://www.thegreengrid.org/~/media/WhitePapers/Green_Grid_Metrics_WP.ashx?lang=en

Figure 8

Cooling load factors for economizer modes compared to baseline



Annual hours - full economizer mode

This is how many hours per year each type economizer mode operates in 100% economizer mode. This analysis is based on a 1MW data center at 50% IT load, located in St. Louis, MO, U.S (the number of hours is highly dependent on geography). The air conditioner bypass via direct fresh air economizer mode provides the least number of full economizer mode hours due to the humidity and dew point conditions required in the data center. The air conditioner bypass via air heat exchanger economizer mode provides 7,074 full economizer mode hours.

Annual hours - partial economizer mode

Partial economizer mode operation occurs when the economizer mode alone is unable to cool the data center due to the outdoor conditions and requires assistance from the compressor. This is a very important attribute for any economizer mode since very few locations around the world allow for operating 100% of the time in economizer mode. In some locations, partial economizer mode hours are much greater than full economizer mode hours resulting in more energy savings derived from partial operation. The air conditioner bypass via direct fresh air economizer mode provides the least number of partial economizer mode hours due to the humidity conditions required in the data center.

Estimated annual PUE

The Power Usage Effectiveness (PUE) is the proportion of total energy used for the entire data center compared to the total energy used by the IT equipment. This annualized estimate is based on a common power infrastructure. The CRAC compressor bypass via second coil economizer mode provides the highest (i.e. worst) annual PUE of 1.39. The air conditioner bypass via air heat exchanger economizer mode provides the lowest PUE of 1.25 in St. Louis.

When considering all the climates in **Figure 8**, air conditioner bypass via air heat exchanger economizer mode provides the lowest PUE in nearly all climates with an average of 1.34. **This represents a 30% lower energy bill for the entire data center compared to the average PUE (1.92) of the baseline system**.

Factors that impact economizer mode operation

There are several factors that influence the number of economizer mode hours available with a particular economizer mode. The dominant factor is the geographic location of the data center. However, the design and set points of the data center's cooling system also have a strong influence.

Geographic location

The use of an economizer mode is completely dependent on the geographic location of the data center. The seasonal conditions of the site will dictate if using an economizer mode is even practical. ASHRAE, The National Renewal Energy Lab (NREL), and The National Oceanic and Atmospheric Administration (NOAA) are just a few sources that provide weather data to assess the number of economizer mode hours available. This data is usually called "bin data" since the weather data is binned into temperature intervals. Using the weather data of a given location, the number of economizer mode hours can be calculated.

Cooling system set points

There are fundamentally two ways to increase economizer mode hours: 1) move the data center to a colder climate, and 2) increase the server inlet design temperature. The first choice is obviously unrealistic for existing data centers. The second choice *is* realistic and is currently being implemented in new and existing data centers. In fact, the 2008 version of ASHRAE Standard TC9.9 increased the maximum server inlet (dry-bulb) temperature from 25°C (77°F) to 27°C (80.6°F). However, how much the IT supply temperature is increased depends on how well the hot and cold air streams are separated.

Separation of hot and cold air streams

Hot and cold air streams in typical data centers tend to mix significantly due to poor rack layout and air management practices. If cooling set points are raised to 27°C (80.6°F) in this scenario, by the time supply air arrives at the server inlet, the temperature would be close to 32°C (90°F). This is why it is common to see cooling system set points significantly below the desired server inlet temperature.

In order to increase cooling system set points and therefore economizer mode hours, hot and cold air streams must be separated. This can be accomplished with either cold aisle containment or hot aisle containment systems. However, hot aisle containment results in significantly more economizer mode hours and therefore is always preferred for new designs. This topic is discussed further in White Paper 135, *Impact of Hot and Cold Aisle Containment on Data Center Temperature and Efficiency*. **Any data center that uses an economizer mode will see a dramatic efficiency gain when a containment system is used. It generally makes little sense to invest in an economizer mode without first investing in a containment system.**

Link to resource
White Paper 135
Impact of Hot and Cold Aisle Containment on Data Center Temperature and Efficiency

Eliminating or reducing non-economizer modes in cooling systems

Historically, economizer modes have been viewed as an additional energy savings feature that supplements the main cooling system. Most designs are created so that the economizer mode can be shut off and the data center will still function in a base cooling mode. However, as data center designs are optimized so that the economizer mode becomes the predominant mode of operation, some new possibilities open up to further improve the cost effectiveness of the data center:

1. If a design allows partial economizer mode even under worst case conditions, such that the primary compressor system is never required to take the full data center load, then there is the possibility of reducing the size of the primary compressor system, saving cost and improving efficiency.
2. If a design allows full economizer mode even under worst case conditions, then it is possible to consider removing the primary compressor system completely and operating the data center always in economizer mode.
3. If a design allows for full economizer mode except for a few worst case conditions, then it is possible to consider placing controls on the IT systems to cap the IT load when the worst case outdoor conditions occur, such that the primary compressor system can be eliminated. Such controls can limit server performance by aggressive power management, or by moving IT loads to a different site

Link to resource
White Paper 136
Ultra high efficiency cooling modules for large data centers

Implementing design characteristics that reduce or eliminate the use of a compressor system can lead to highly efficient data center cooling systems. White Paper 136, *Ultra high efficiency cooling modules for large data centers*, discusses a new approach for cooling data centers that uses approximately half the energy of traditional methods, yet provides greater scalability, availability, and ease of maintenance.

Conclusion

In the past, cooling system economizer modes have not been seriously considered in most data centers. This was largely due to the lower cost of electricity, lower IT equipment supply temperatures, and non-existent carbon emission regulations. Today, standards such as ANSI/ASHRAE Standard 90.1-2010, and regulations such as the UK Carbon Reduction Commitment, are pressuring data centers into lowering energy use. Certain economizer modes are an effective means at reducing energy use in many climates. Data center operators in some climates are finding that economizer modes can operate as the primary cooling system allowing the mechanical system to serve as the secondary or backup.

In certain climates, some economizer modes can save over 70% in annual cooling system energy costs, corresponding to over 15% reduction in annualized PUE. However, with at least 15 different types of economizer modes with imprecise industry definitions, establishing a terminology for describing the different types of economizer modes is essential in order to compare, select, or specify economizer modes. The terminology and definitions proposed in this paper along with the qualitative and quantitative comparisons across the different types of economizer modes, helps data center designers make better decisions.

About the authors

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Resources

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White Paper 59

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