The Changing Landscape of Chillers' Energy Efficiency

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ABSTRACT

Chiller technology is decades old; however, it is still an evolving technology. Improvements in chiller technology range from its control, sound, and reliability to the all-important aspect of its energy efficiency. This article explores how the evolving efficiency levels of chillers are changing the landscape and the dynamics of chiller systems.

INTRODUCTION

Chiller Systems' Industry Trends

The water-cooled centrifugal chillers' market has historically occupied the largest market segment among chillers. However, this trend has been reversed towards air-cooled chiller systems in the past few years. Figure 1 from the *Air-Conditioning, Heating and Refrigeration Institute* (AHRI) shows the market trends for water-cooled and air-cooled chillers in the United States over the past three decades. The most recent AHRI data show the same trend as well [1].

There may be different reasons behind this shift in the industry dynamics from water-cooled systems towards air-cooled ones. One of the reasons may be economical. Recent studies have shown that the total cost of ownership (TCO) for air-cooled systems is lower than that for water-cooled ones [3][4][5]. Ease of operation and lower maintenance cost may be other reasons why more owners and plant operators are shifting to air-cooled chiller systems [6]. Global water scarcity may be yet another major reason for this shift in many regions as shown in Figure 2. There may also be environmental reasons behind this industry dynamic. These may include the environmental ones related to publicly owned treatment

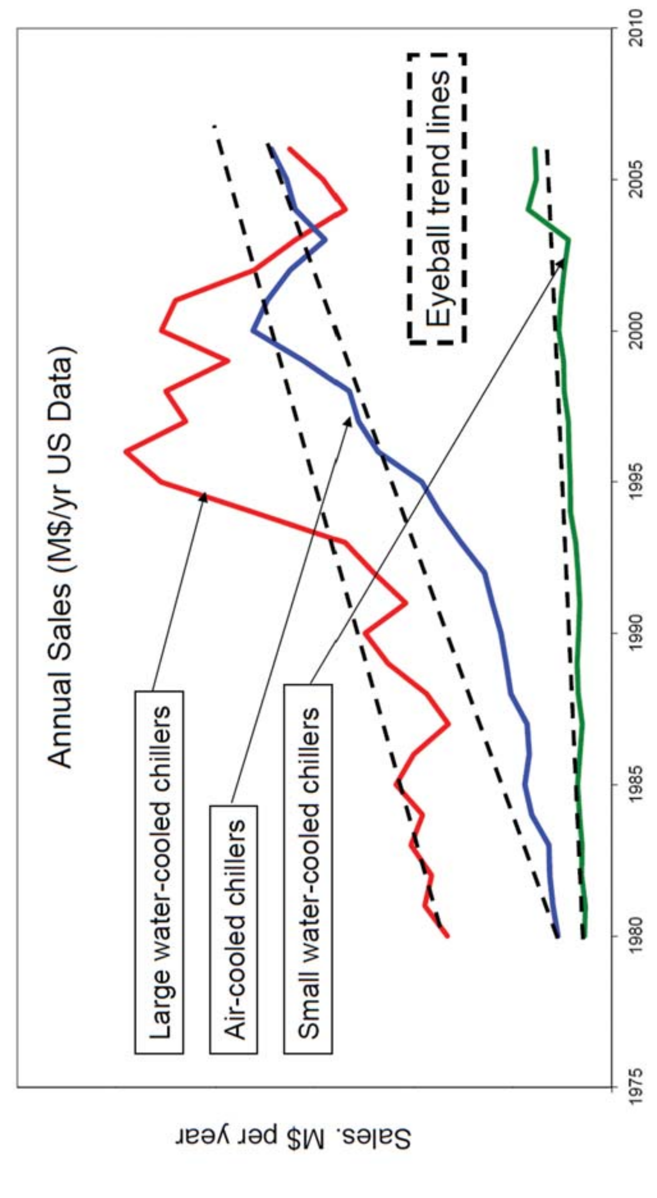


Figure 1. U.S. Chiller Market Trends [2] [*]

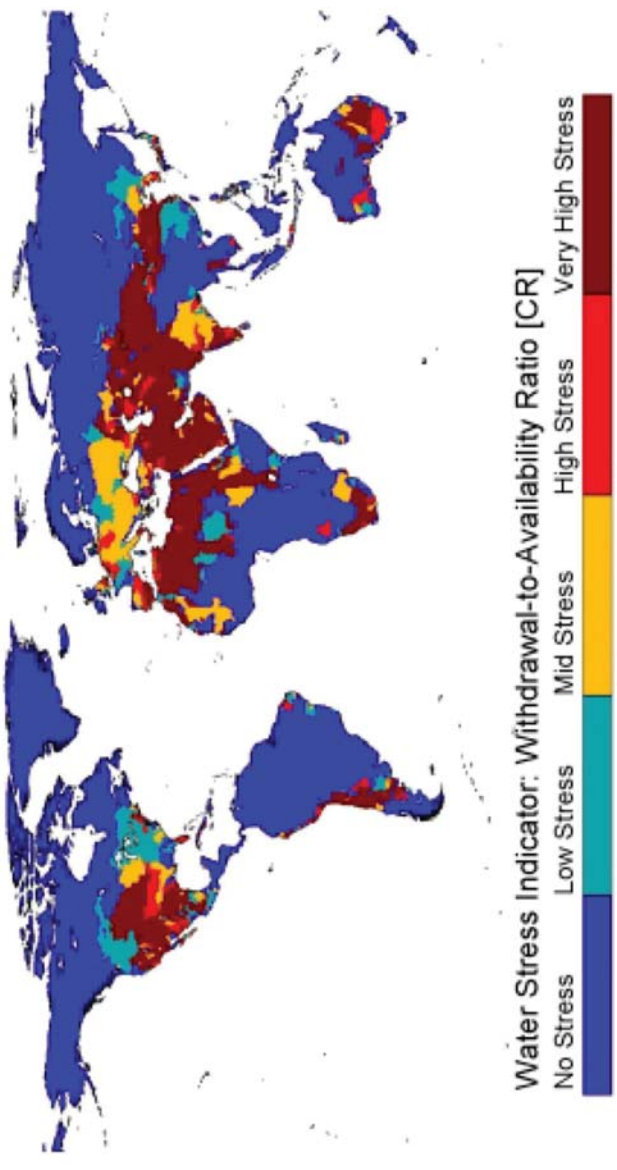


Figure 2. Water Stress Worldwide [10]

works (POTW), water disposal regulations [7], or mitigating health risks associated with *legionella* disease [8] [9].

This article tries to look at another subtle facet of this industry shift: the changes in energy efficiency levels of the mid-range chillers. On the following pages, we examine how the improvements in air-cooled chiller energy efficiency levels may have contributed to this market shift by eroding and eating into the low-end water-cooled efficiency market segments.

MAIN BODY

The Efficiency Landscape

ANSI/ASHRAE/IESNA Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings* references the minimum efficiency requirements for chillers when rated according to AHRI Standard 550/590, *Performance Rating of Water Chilling Packages Using the Vapor Compression Cycle*. Air-cooled screw chiller efficiency values shown in Figure 3 represent a survey of published cataloged data from the four largest chiller manufacturers in the United States, representing an estimated 90% or more of the AHRI chiller market [11].

The graph shows a distinctive premium high efficiency air-cooled chiller market with a significant energy efficiency improvement over the minimum requirements of Standard 90.1 [***]. To see the effect of this premium high efficiency segment on the chiller systems' industry dynamics, a comprehensive set of energy simulations were run.

Energy Modeling

The energy model used in all the energy simulations was the *Large Office* model from the *DOE Commercial Building Benchmark Models* as developed by the *U.S. Department of Energy* (DOE), *Lawrence Berkeley National Laboratory* (LBNL), *Pacific Northwest National Laboratory* (PNNL), and *National Renewable Energy Laboratory* (NREL) under the *Net-Zero Energy Commercial Building Initiative* [12]. All energy runs were done using the latest publicly available version of *EnergyPlus* (4.0.0), also developed by the DOE and the *National Renewable Energy Laboratory* (NREL). An office building model was used since office buildings represent the largest single energy-consuming building sector, as shown in Figure 4.

A total of seventeen different climate zones were modeled, covering the entire spectrum of global climate conditions. They covered the DOE

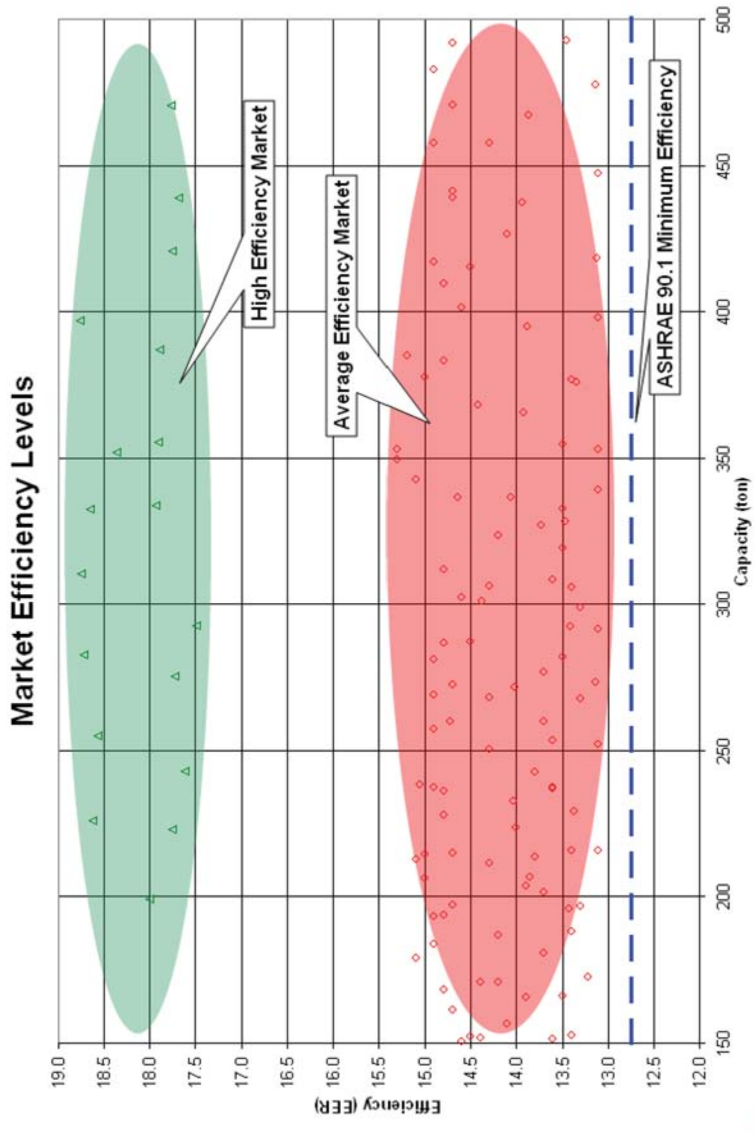


Figure 3. Screw Air-cooled Chiller Market IPLV Efficiencies (ASHRAE Standard 90.1-2007 [**])

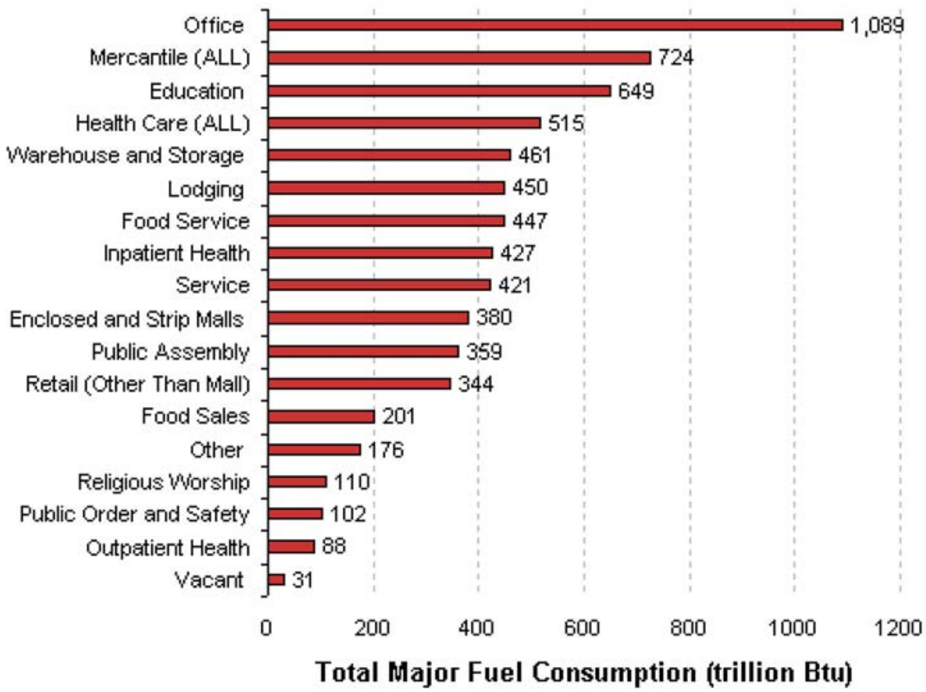


Figure 4. Commercial Buildings' Energy Consumption by Sector [13]

fifteen climate zones in the United States as shown in Figure 5.

In addition, two climate zones not represented in the U.S. were also modeled using international cities. These two international climate zones were: Climate Zone #1B (Very Hot + Dry) as represented by Riyadh, Saudi Arabia, and Climate Zone #5C (Cool + Marine) as represented by Vancouver, British Columbia, Canada.

A total of four different chiller efficiency levels were used:

— Standard 90.1 minimum air-cooled efficiency for screw chillers
— Standard 90.1 minimum water-cooled efficiency for centrifugal chillers
— Industry premium high efficiency air-cooled efficiency for screw chillers
— Industry premium high efficiency water-cooled efficiency for centrifugal chillers

The models used chiller efficiencies as per the latest requirements of

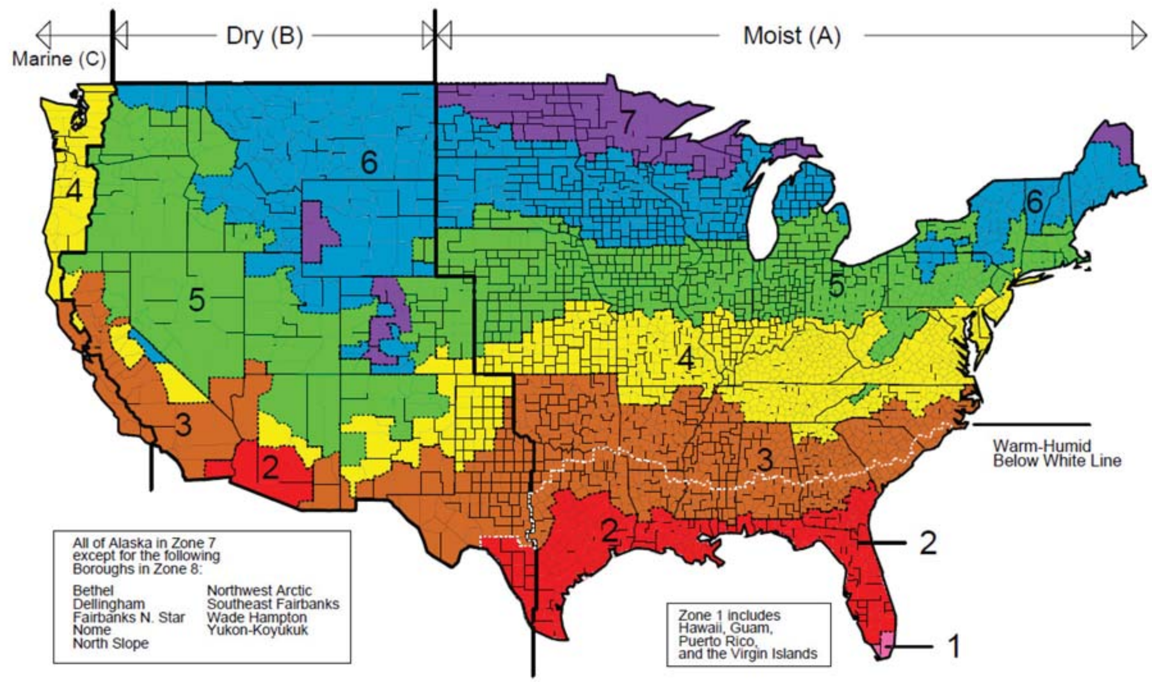


Figure 5. DOE Climate Zones in the United States

ASHRAE Standard 90.1-2007 (1/1/2010 values based on 2008 *addenda m*). This reference standard was used since it is the benchmark for most building codes mandated in the different states, as show in Figure 6.

Crossflow, axial fan-cooling towers with variable-speed drive (VSD) fans were used in the model for water-cooled chiller condensers' heat rejection. Variable speed condenser water pumps were also used [****]. Differential enthalpy air-side economizers were used in climate zones 2B, 3B, 3C, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 7, and 8 as per Standard 90.1 requirements.

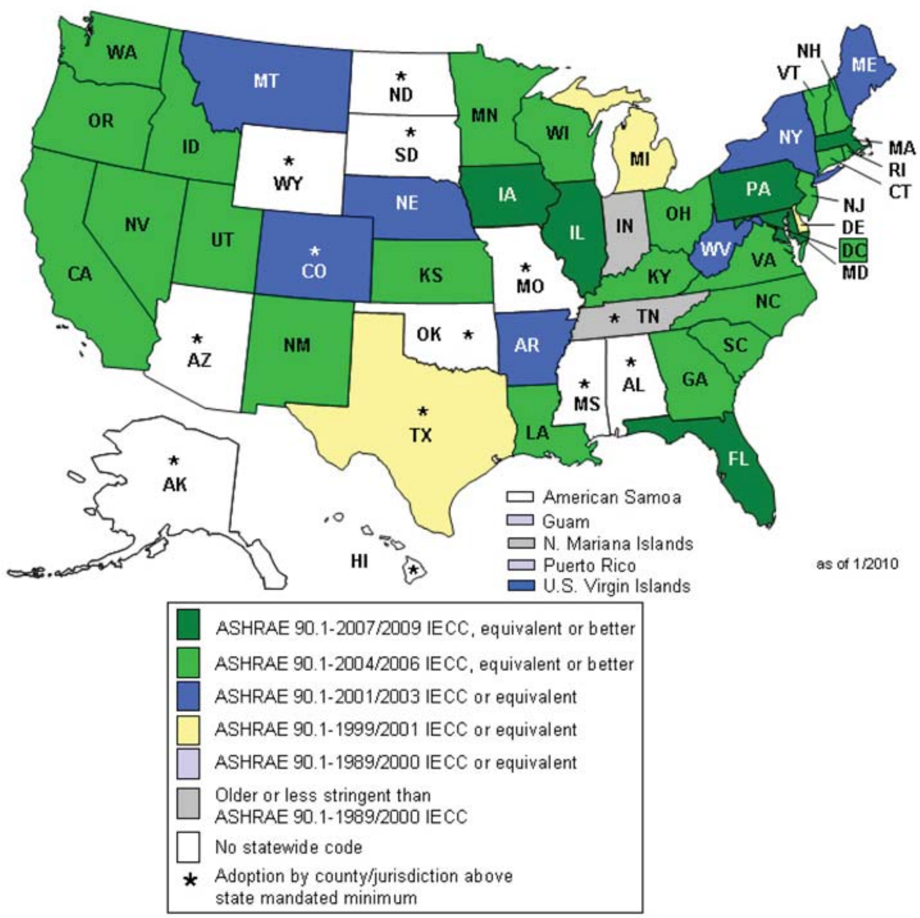


Figure 6. Status of Commercial Energy Codes Relative to ASHRAE Standard 90.1 [14]

Single chiller plants were used in all simulations to standardize the comparison. The chiller plant nominal capacity for all simulations was 400 tons (1,407 kW). Chiller model details are listed in Table 1.

The Results

Figures 1—17 show the comparison between air- and water-cooled chillers with ASHRAE Standard 90.1 minimum efficiencies versus the premium high efficiency air-cooled and water-cooled chillers across all seventeen climate zones. As can be seen from the comparisons, the premium high efficiency air-cooled chillers outperform the minimum water-cooled chiller systems across all climate zones.

Table 1. Chiller Model Details

Variable	Water-Cooled	Air-Cooled
Peak Load	400 tons (1,407 kW)	400 tons (1,407 kW)
Plant Configuration	▪ Single Centrifugal Chillers ▪ Single Cross-Flow Tower ▪ Single Condenser Pump	▪ Single Screw Chiller
Chiller Full Load Efficiency (at AHRI 550/590 conditions)	▪ Standard 90.1 minimum: **6.100 COP (0.576 kW/ton)** ▪ High Efficiency: **6.620 COP (0.531 kW/ton)**	▪ Standard 90.1 minimum: **2.802 COP (1.255 kW/ton, 9.562 EER)** ▪ Premium High Efficiency: **3.230 COP (1.089 kW/ton, 11.023 EER)**
Chiller IPLV (at AHRI 550/590 conditions)	▪ Standard 90.1 minimum: **6.401 COP (0.549 kW/ton)** ▪ High Efficiency: **10.887 COP (0.323 kW/ton)**	▪ Standard 90.1 minimum: **3.737 COP (0.941 kW/ton, 12.750 EER)** ▪ Premium High Efficiency: **5.497 COP (0.640 kW/ton, 18.760 EER)**

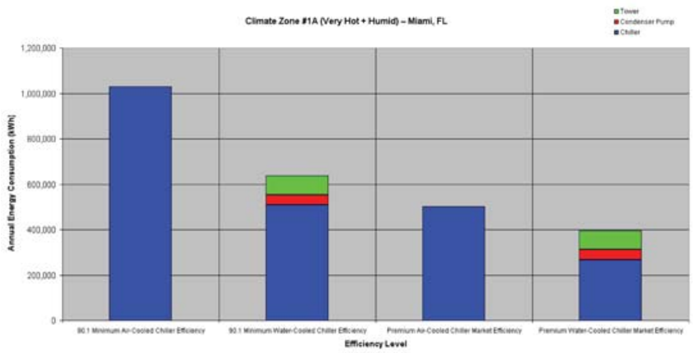


Figure 7. Annual Energy Consumption in Climate Zone #1A (Very Hot + Humid)—Miami, Florida

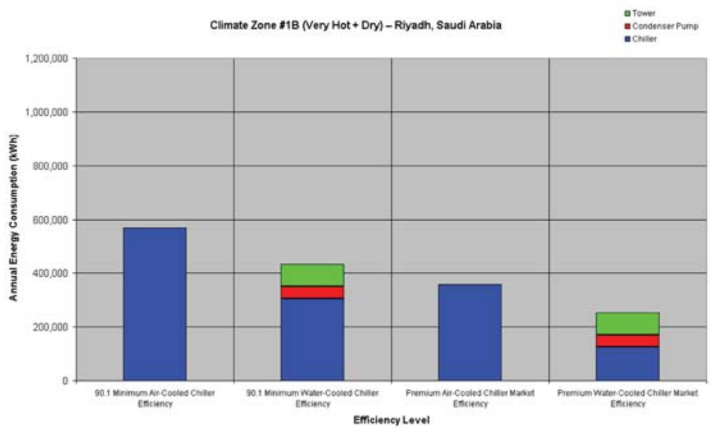


Figure 8. Annual Energy Consumption in Climate Zone #1B (Very Hot + Dry)—Riyadh, Saudi Arabia

Figure 9. Annual Energy Consumption in Climate Zone #2A (Hot + Humid)—Houston, Texas

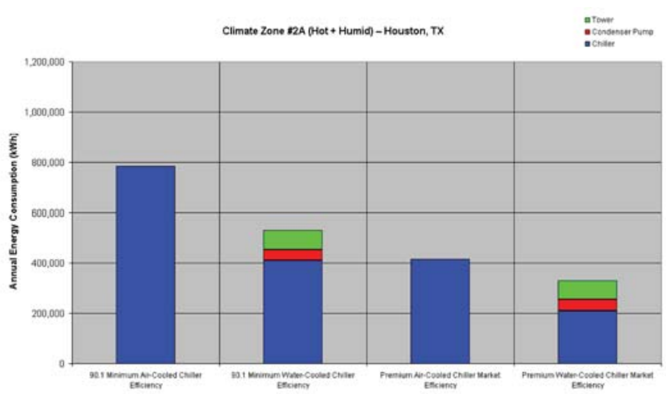
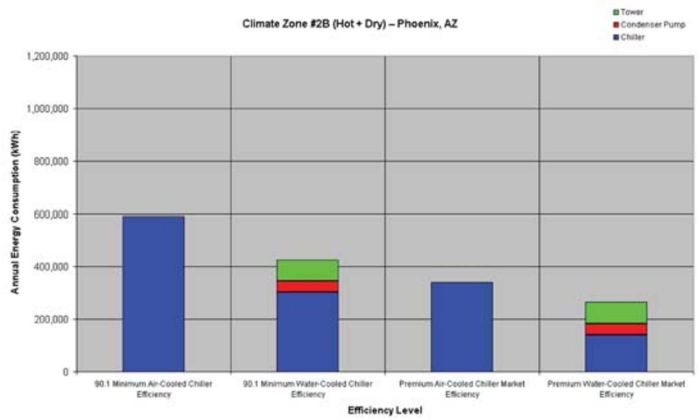


Figure 10. Annual Energy Consumption in Climate Zone #2B (Hot + Dry)—Phoenix, Arizona



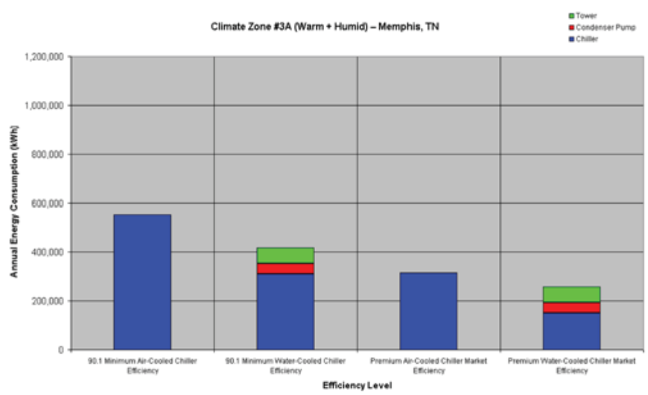


Figure 11. Annual Energy Consumption in Climate Zone #3A (Warm + Humid)—Memphis, Tennessee

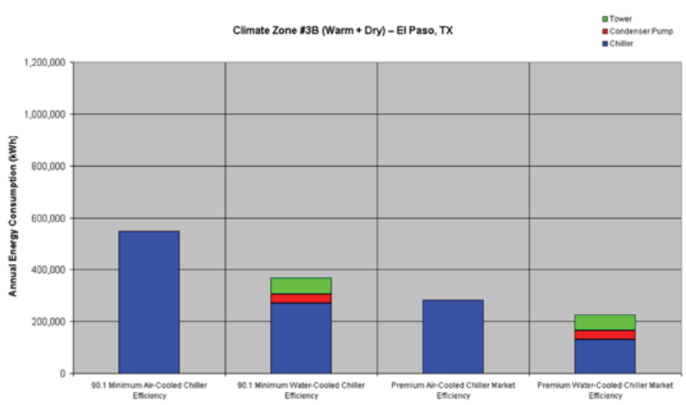


Figure 12. Annual Energy Consumption in Climate Zone #3B (Warm + Dry)—El Paso, Texas

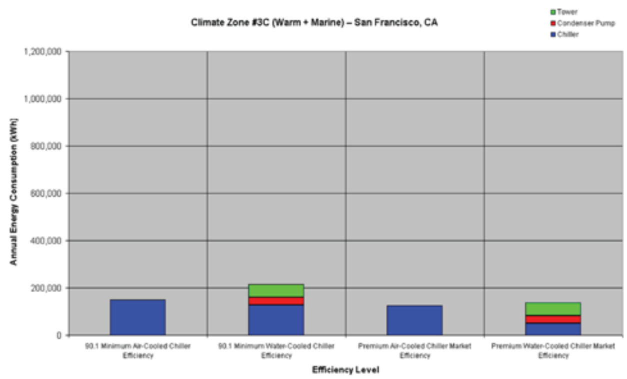


Figure 13. Annual Energy Consumption in Climate Zone #3C (Warm + Marine)—San Francisco, California

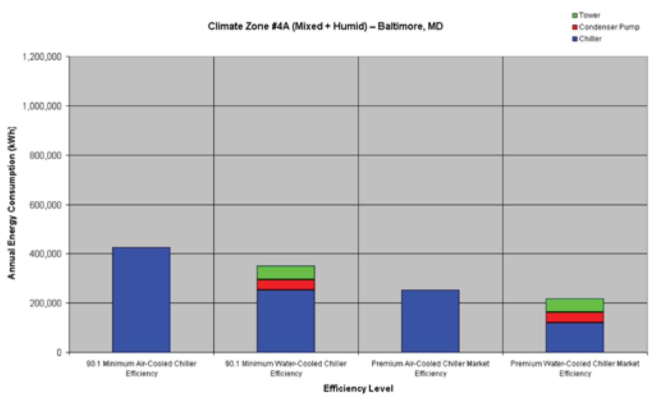


Figure 14. Annual Energy Consumption in Climate Zone #4A (Mixed + Humid)—Baltimore, Maryland

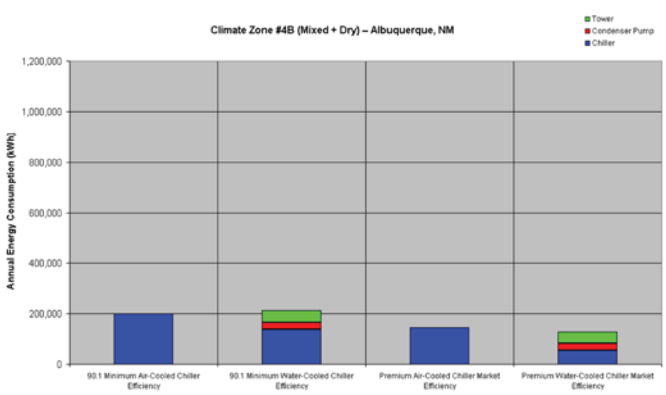


Figure 15. Annual Energy Consumption in Climate Zone #4B (Mixed + Dry)—Albuquerque, New Mexico

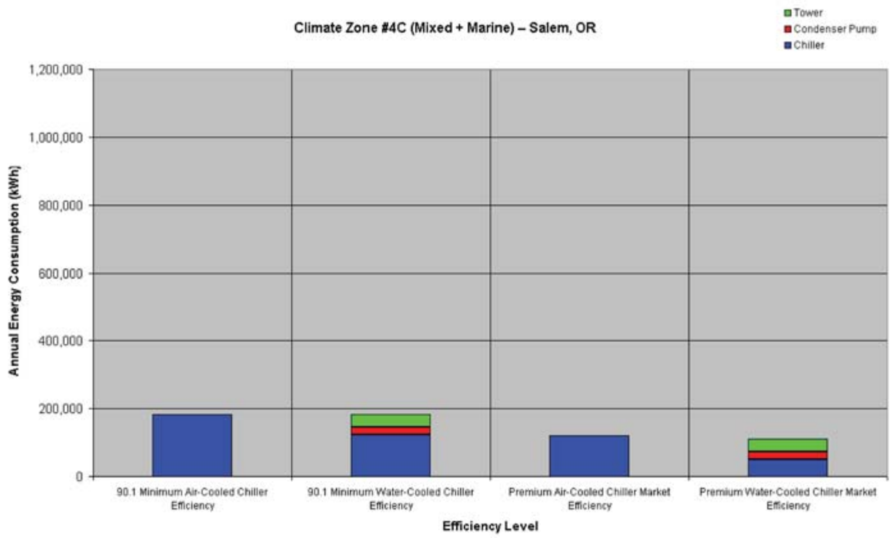


Figure 16. Annual Energy Consumption in Climate Zone #4C (Mixed + Marine)—Salem, Oregon

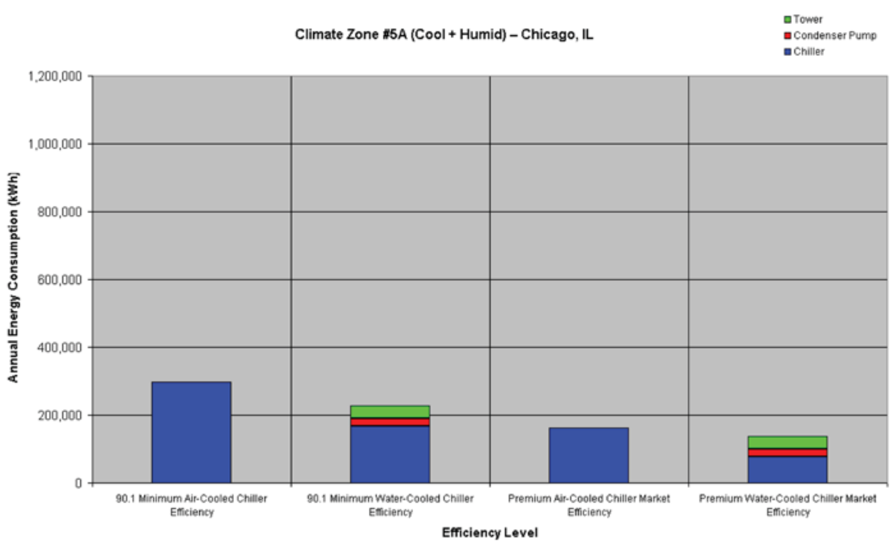


Figure 17. Annual Energy Consumption in Climate Zone #5A (Cool + Humid)—Chicago, Illinois

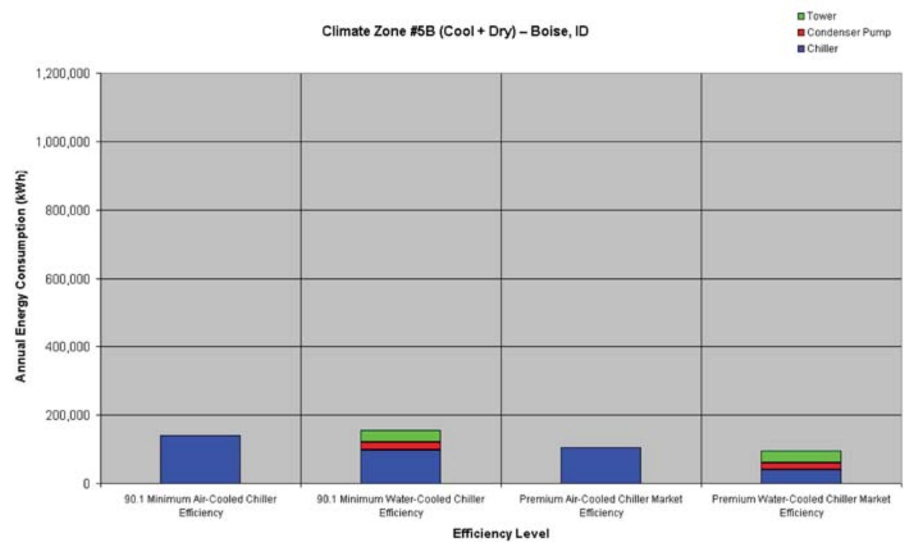


Figure 18. Annual Energy Consumption in Climate Zone #5B (Cool + Dry)—Boise, Idaho

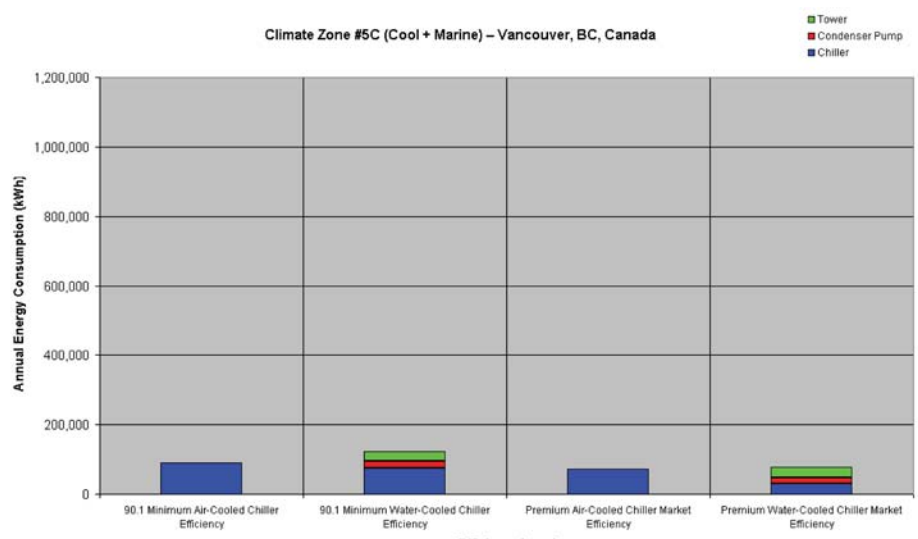


Figure 19. Annual Energy Consumption in Climate Zone #5C (Cool + Marine)—Vancouver, British Columbia, Canada

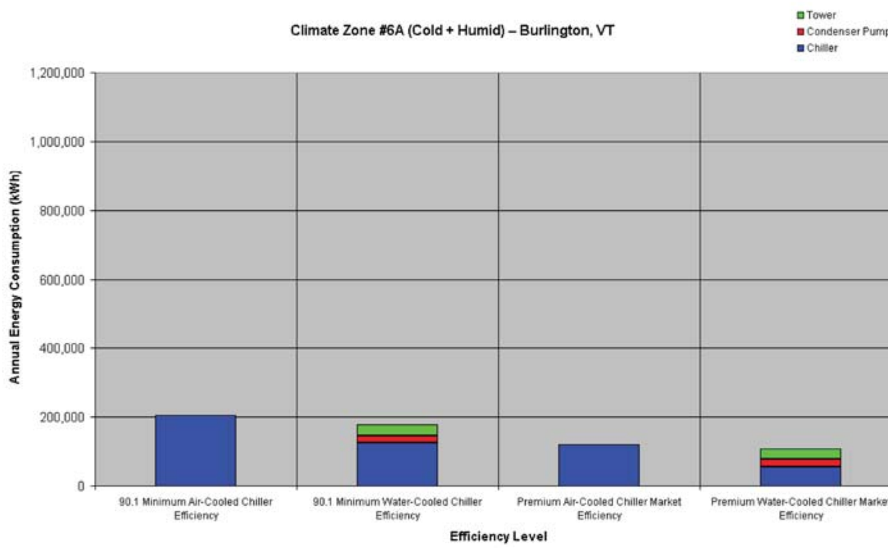


Figure 20. Annual Energy Consumption in Climate Zone #6A (Cold + Humid)—Burlington, Vermont

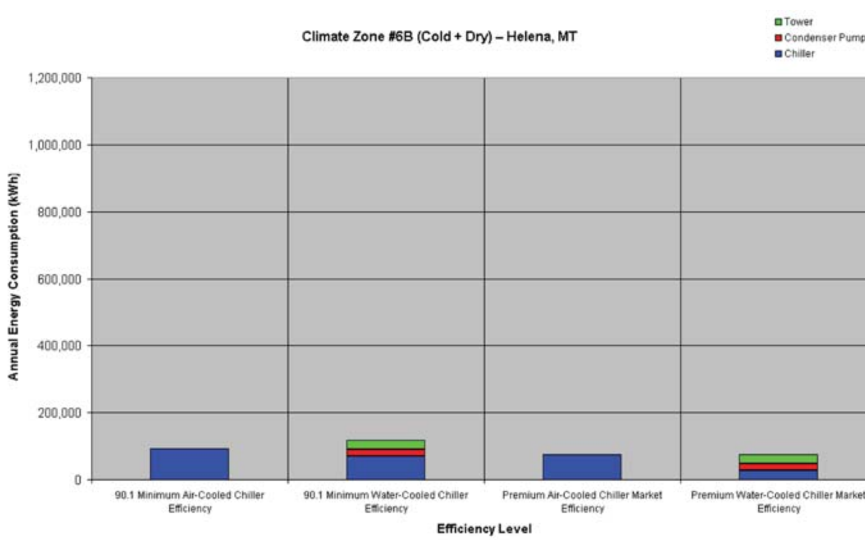


Figure 21. Annual Energy Consumption in Climate Zone #6B (Cold + Dry)—Helena, Montana

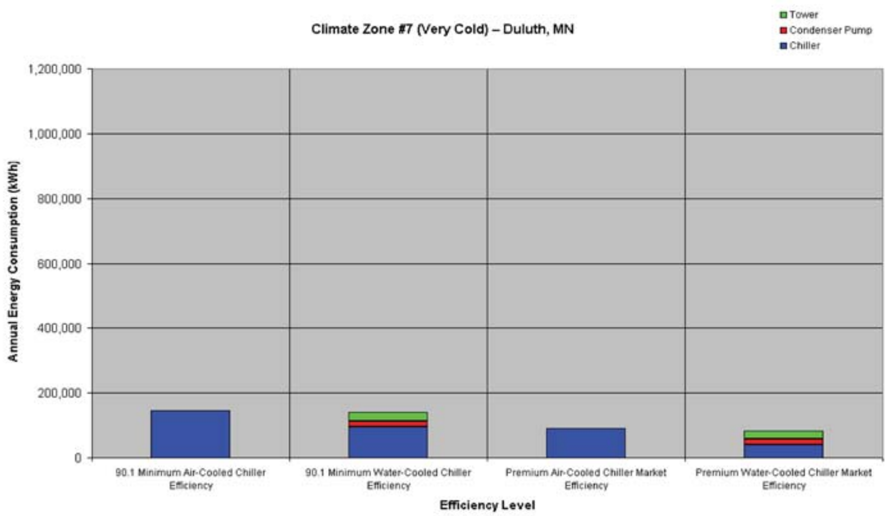


Figure 22. Annual Energy Consumption in Climate Zone #7 (Very Cold)—Duluth, Minnesota

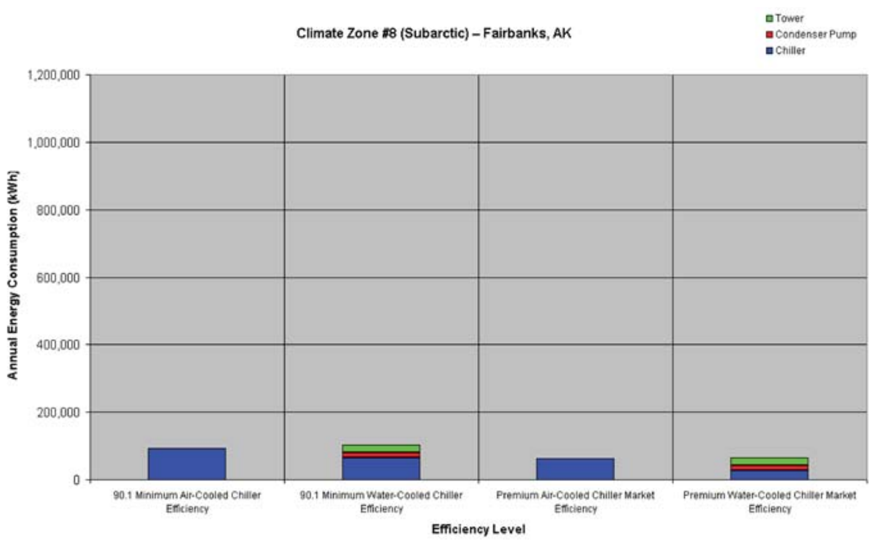


Figure 23. Annual Energy Consumption in Climate Zone #8 (Subarctic)—Fairbanks, Alaska

CONCLUSION

Survival of the Most Efficient (and economical!)

The energy comparisons outlined in the article are between four different systems:

— Standard 90.1 minimum air-cooled chiller system
— Standard 90.1 minimum water-cooled chiller system
— Best-in-class air-cooled chiller system
— Best-in-class water-cooled chiller system

The results of the energy model on these pages may have revealed yet another reason why the air-cooled chillers industry segment has outgrown its water-cooled sister (or brother!). Engineers and owners who are looking for systems that just meet the minimum energy requirements of Standard 90.1 may have switched to air-cooled chiller systems instead of water-cooled ones. This is because the premium high efficiency air-cooled chiller industry can deliver better energy performance than an equivalent water-cooled system that is just meeting code requirements.

An important note is due here. Premium high efficiency air-cooled chillers may not be the silver bullet answer to all systems. Water-cooled chillers have a premium efficiency market segment of their own as well. On the one hand, the previous analysis showed that the premium high efficiency air-cooled chillers are more energy efficient than the minimum code-compliant water-cooled chiller systems; on the other hand, the analysis also showed that the high efficiency water-cooled chillers do deliver the best overall energy efficient systems.

What can we read from this picture, along with the industry trend we discussed in Figure 1 above? One interpretation of this trend may be that engineers and owners who are looking for efficient systems that are cost competitive are shifting towards the premium high efficiency air-cooled chillers. Premium high efficiency chillers provide a cost effective option to such industry sectors, with energy performance that is superior to the minimum code-compliant water-cooled chiller systems. At the same time, engineers and owners with less budget restriction who are looking for the most efficient, best-of-class system will most likely opt for the high efficiency water-cooled chiller systems, as they surpass all others, which the analysis has shown.

Closing Thoughts

Darwin taught us that it's neither the strongest nor the most intelligent species that survive; it's those that adapt best to changes in the environment [15]. The idea and the aim behind the analysis presented here was to try and understand the continuing industry shift from water-cooled chiller systems to air-cooled chiller ones. The analysis indicated that there are, in fact, green energy efficiency and energy conservation reasons behind this shifting of industry dynamics beyond the economical, maintenance, and environmental aspects explored in other articles as noted earlier. The premium high efficiency air-cooled chillers in our air-conditioning industry today surpass the efficiency of water-cooled systems that just meet energy codes minimum requirements. Such shifting marketplace needs and trends that continue to be rebuilt have to be mirrored in system designs, industry standards, and local building codes at large if they are to stay relevant, useful, and reflective of the true picture in an ever-changing and ever-evolving industry.

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Footnotes

[*] No Dollar values are shown on the vertical axis of the graph as per AHRI confidentiality requirements.

[**] ASHRAE Standard 90.1-2007 is used. Chiller efficiencies referenced here are based on the latest publicly available addenda to the Standard (2008 Supplement—addenda m): Table 6.8.1C Water Chilling Packages-Efficiency Requirements as of 1/1/2010. Path A was used.

[***] Constructing a similar market picture for water-cooled centrifugal chillers is not as straightforward and maybe practically impossible. This is due to the virtually infinite compressor impeller sizes, quantity of evaporator copper tubes and shell combinations. However, it is safe to state that the premium efficiency level for water-cooled centrifugals would be in the range of 0.3 IPLV / 6.6 COP.

[****] ASHRAE Standard 90.1 requires only a two-speed fan control on the tower and does not specify condenser pump drive control, however, VSD motors were used here since some jurisdictions now require them anyhow for all motors above certain size (5 HP in California for example as per *California Code Of Regulations Title 24—2008 Building Energy Efficiency Standards*). The new version of ASHRAE Standard 90.1 (2010) is planned to have VSD tower as a mandatory requirement. Interestingly though, there wasn't any significant energy savings from using VSD versus two-speed motor controls in the different energy simulations across the seventeen climate zones.

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