Predictive Maintenance based on Performance Analysis using System Efficiency Index and Sub-Efficiencies is the future

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ABSTRACT

HVACR equipment uses 20% of global electricity, whilst the pressure to reduce energy consumption and peak power demand is ever-increasing. The focus on efficiency has targeted product standards and ratings whereas the importance of commissioning and maintenance has been neglected. Effective methods to document field performance is a critical pre-requisite to improve operating efficiency and reliability. COP and Seasonal Performance Factor (SPF) values that change by 2-5% for each degree of operating conditions are wholly impractical to benchmark water chillers, heat pumps and refrigeration systems (RACHP - systems). The increasing number of sensors within equipment and the "Internet of Things" (IoT) opens up good opportunities for predictive maintenance through automated analysis. Experience is built on a large number of systems to facilitate predictive maintenance and optimisation of many plants. Thermodynamic analysis to establish System Efficiency Index (SEI), and Sub-Efficiencies for the compressor, condenser and evaporator offer powerful KPIs. This paper presents the experience gained from the use of SEI and Sub-Efficiencies in predictive maintenance and efficiency optimisation.

Keywords: Predictive Maintenance, Air Conditioning, Refrigeration, Heat Pumps, Optimisation, System Efficiency Index, SEI, Compressor efficiency and Performance Analysis. RACHP – Refrigeration, Air Conditioning & Heat Pumps.

1. INTRODUCTION

It is often not realised how important RACHP technology is for today's society. Everybody benefits from the technology as we eat and live. Active cooling is a part of most production processes and productivity, as well as comfort being dramatically improved with air conditioning. Additionally, heat pumps are progressively playing an increasing role to reduce the primary energy used for heating. It is estimated that 20% of global electricity is used for refrigeration processes, with air conditioning the largest consumer. Other large sectors are supermarkets and the food and drinks industry, each believed to use around 4% of global electricity. In spite of efficiency improvements, Data Centres are rapidly increasing electrical demand, as the growth in this sector is much faster than the efficiency improvements. Our industry has previously been in focus for our environmental impact due to ozone depletion and we made the necessary technology changes, moving from CFC and HCFC refrigerants to chlorine-free refrigerants. Today, the use of ammonia, CO_2 and hydrocarbons are increasing rapidly.

The future challenge is to reduce the carbon footprint caused mainly by energy consumption of RACHP systems as the direct impact on global warming of refrigerants continues to decrease. Specifications today generally demand high efficiency equipment but there are huge differences between predicted energy consumption in the original design and the actual energy consumption realised. It is assumed that equipment complying with high rating standards installed by competent contractors will operate efficiently. Unfortunately, this is rarely achieved.

A significant difference between modelled energy performance and that measured has been identified in many surveys and there is an increasing focus on Measurement and Verification (M&V) in Green Building Schemes, but the practical impact on efficiency is still limited. The purchasing process, with contractors and sub-contractors fulfilling the specification of each separate contract, often leave the operating efficiency of the final system to on-site staff without realistic capabilities to achieve the efficiency target**.**

The results of performance monitoring of thousands of sites with a total cooling capacity of several thousand MW, confirms that most water chillers, heat pumps and refrigeration systems are working far

below optimum efficiency. Savings of 10-30% are achievable through simple correction of faults and system optimisation at either low or no investment at all.

Many design and installation contracts have been fulfilled without delivering the expected performance.

Various theories on the causes are frequently based on assumptions rather than measured and documented facts, as there are many parties involved and often there is not a clear breach of specification that causes efficiency problems. In most cases, only the symptoms are known, not the cause. Monitoring-based performance analysis minimises the cost of commissioning, trouble shooting and optimisation and puts a sound platform for predictive maintenance in place.

2. MONITORING BASED "CONTINOUS COMMISSIONING" IS COST EFFECTIVE

Commissioning procedures and M&V requirements are rarely on a level that pinpoint problems, and in most projects, there is nobody with the competence or experience assigned the responsibility (paid) to ensure performance over time and over varying operating conditions. Specified rating and benchmarking parameters such as Coefficient of Performance (COP), Integrated Part Load (IPLV), Seasonal Performance Factor (SPF) or Seasonal COP (SCOP) are expected to ensure efficient operation. In fact, these might specify efficient products and designs, but often fail to ensure efficient operation. These do not include sufficient information and details for commissioning or optimisation as they do not establish the information required to compare conditions occurring in a dynamic plant with the intended design. The information used in the design process to predict efficiency and energy consumption is rarely available to those working with maintenance and operation.

Commissioning, as well as maintenance and optimisation, requires key data from the design process to document if low efficiency is due to plant degradation or poor system balancing, to allow direct benchmarking versus design. This said, it is key to understand that a system running at design data conditions is not optimum operation. It is common that systems are maintaining higher temperature lifts than what is actually required, only because "that is the specification". It is traditional to design with a margin introduced in each step of the process, as the key success factor for everybody involved is that the right temperature is achieved. To some extent this can be good, as there are then possibilities to reduce temperature lift below design. Further, most systems should operate with floating chilled water/evaporation temperatures and floating condensing/coolant temperatures, as this realises significant energy savings. **Oversized systems running at design conditions are not desirable nor cost-effective.**

In Annex 52 of International Energy Agency (IEA), work is in progress to develop guidelines for "Long term performance measurement of GSHP Systems serving commercial, institutional and multi-family buildings" (IEA, 2021). Although the focus in this work is for Ground Source Chiller/Heat Pump Systems (GSHP), it is obvious that the strategies developed are useful in almost any system using a vapour compression process that moves energy between a heat source and heat sink. The key is to optimise the performance of each sub-system as a part of the total system under varying conditions, not each sub-system to a steady state design condition.

To make design, commissioning and performance analysis cost effective, the following parameters are of key importance:

- **Climate** at the site location for a "normal year" that includes the number of hours at each outdoor temperature
- **Cooling load** as a function temperature and the expected variations over days/weeks. This will generate a cooling/heating energy signature that will form the basis for calculations.
- **Temperature of media that cools the condenser** as function of ambient temperature
- **Temperature of media cooled by the evaporator** as function of ambient temperature
- **Design of installed heat recovery**, where applicable
- **Design of free cooling**, where applicable
- **Performance data of chiller/heat pump/refrigeration unit** across the operating envelope

These inputs are important for specifications and essential in order predict energy consumption. Having this available during commissioning, optimisation and performance analysis allows comparison of each part of the system against the design criteria at each ambient temperature.

2.1. Actual operation will always be different from design

Seasonal performance factors/COP are affected by so many factors that it is almost impossible to hold any contractor responsible for deviations in operating performance, unless the background data is available. Deviations are inevitable, such as:

A. **Building load is not as designed.** The use of buildings will rarely be identical to what was intended when the project design was undertaken. The load often changes, with the tenants using more computers or lighting and the number of people using the building also changes.

B. **Climate will not be same as a "normal year".** Deviations in performance cannot be accurately compensated by degree days where chillers and/or heat pumps are involved. "Degree Hours" might be relevant for heating with boilers, district heating and direct electrical heating where temperature levels and humidity can be neglected. For systems where the COP is dependent on outdoor temperature and humidity, it is not sufficient to execute a simple adjustment between indoor and outdoor temperatures.

C. **The temperature level in heating and cooling circuits are not as designed.** This has a major impact upon performance and set points are often controlled by onsite staff and/or maintenance staff. As every degree change in temperature lift represents 2%-5% difference in COP, it is often found that a change at the Building Management System (BMS) causes changes of 20% in COP at the chiller/heat pump without anybody having a clue of the importance of the set-points. It is not unusual that what were intended to be temporary adjustments are left permanently. A change of chilled water supply temperature of only 2K can save 10% in energy use and running costs.

D. **Control requires adaptation to time constants in system.** In almost all systems there is an interaction between the chiller/heat pump/refrigeration system internal controls and the building BMS. The interaction between equipment controllers for pumps, fans, chillers and heat pumps are key for efficient operation. All systems are exposed to loads starting at zero that eventually reach a peak load. The peak load is frequently lower than the peak design load, due to the implementation of safety margins. Focus is often directed toward performance at full capacity and the design conditions, whereas this has little or no influence on annual energy consumption, nor reliability, as those conditions might never occur and if these do, it is only for few hours per year.

These days, it is common that sensors required for cost-effective performance analysis, commissioning, optimisation and predictive maintenance are available, but that monitoring is often structured to simply issue a fault alarm only when it has already occurred.

3. THERMODYNAMIC METHOD FOR PERFORMANCE BASED COMMISSIONING, PERFORMANCE ANALYSIS AND PREDICTIVE MAINTENANCE

This paper is based on 15 years of experience with the web-based "IoT" platform, **ClimaCheck *online***, a dedicated performance analysis platform for the optimisation and predictive maintenance of air conditioning, heat pumps and refrigeration systems. The performance analysis method used is based on the thermodynamic calculations of the refrigeration process (Fahlén, 1989) (Berglof, 2005). The method is strictly based on un-biased thermodynamics and does not require any equipment manufacturers product data. The data measured and recorded includes the pressures and temperatures within the refrigerant circuit and the electrical power input to the compressor, as is shown for a basic process in (Figure 1). This method can be used for any vapour compression refrigeration process and also includes the calculation of the cooling capacity and COP of direct evaporation systems with multiple evaporators and/or condensers, where conventional methods are not applicable. There are several advantages with the thermodynamic method for performance analysis versus conventional methods based on air flow/water flow rates/temperature measurements only, e.g.:

1. The thermodynamic analysis provides performance at a component level, essential for the true understanding of system operation and optimisation. The COP, cooling capacity and total system efficiency are calculated, as well as sub-efficiencies for the compressor, evaporator and condenser.

2. The much lower sensitivity for measurement errors, where pressures and temperatures are used to establish the system refrigerant enthalpy values, versus using a small water or air temperature difference to calculate a very large cooling capacity. Air-based systems must also take into account humidity/moisture contents for such calculations.

3. Thermodynamic analysis is conducted independently for each refrigerant circuit, whereas air or water flow-based measurements are usually based only on the total cooling or heating capacity, which cannot pinpoint problems or deviations within each of multiple refrigerant circuits.

4. Thermodynamic analysis is often lower in cost than flow-based measurements based on water or air flow, in particular if integrated within the BMS from outset.

The thermodynamic method allows measurement of COP with an uncertainty of less than 5%. The total System Efficiency Index (SEI) compares measured COP with a loss free “Carnot” process (Lane Anna-Lena, 2014). This accuracy is hard to achieve with flow-based measurements in field applications, whereas the detailed sub-efficiency information facilitates immediate understanding of what works well and where there is room for improvement. It is also possibly to identify sensor deviations, as a refrigeration process is well defined and the relation between pressure and temperatures in a circular process are closely related. So, a measuring error is detected before it results in costly trouble-shooting or performance drift.

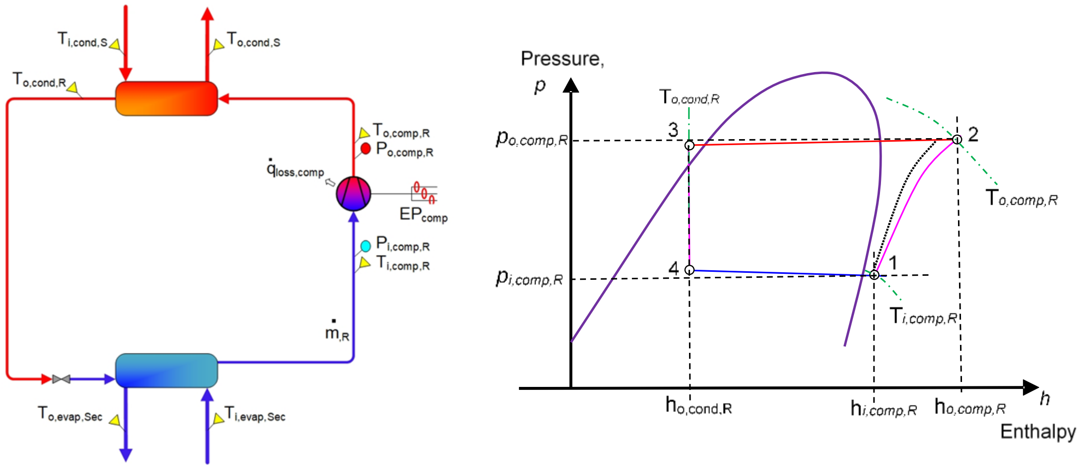

Figure 1. Sensor required to analyse capacity and performance of a refrigeration process and the points defined in a pressure enthalpy graph

4. WEB-BASED MONITORING (IoT) FACILITATE THAT ALL KEY PERFORMANCE INDICATOR (KPIs) ARE ANALYSED IN REAL TIME

Conventional commissioning and maintenance works are typically conducted at the time defined by the contract requirements and when the service organisation has spare capacity, whereas with continuous performance analysis, data is collected and analysed 24/7, in real time. System deviations are then detected as soon as these occur. Receiving detailed data occurring from all operating conditions enables one to correlate the measured data against the design criteria. Experience from thousands of sites clearly shows significant problems at common load conditions, as commissioning in the best cases was executed at one or a few operating conditions. Even worse, commissioning of many installations is conducted before the system is in full use and at whatever ambient conditions occur at the date scheduled for commissioning inspections. With many different contractors being responsible for their own specification, it is common that limited attention is given to thorough optimisation. Due to tight time constraints and strong incentives to complete and hand over each project for operation, what should be seen as a serious problem will often be accepted or neglected as a minor issue, as the consequences are not understood.

To cost-effectively work with optimisation, a measurement strategy is essential, as the alternative is to spend many hours on site to figure out what the real problems are. To afterwards extract data from the BMS and/or chiller/heat pump controllers is time consuming and frequently challenging, as important data is often missing, and sample rates are not correlated or sufficient.

With a planned strategy for M&V, it is possible to see all KPIs in real time, these being monitored and visualised, thus making it possible to identify any deviations as they occur. Introducing IoT allows the monitoring of a large number of plants with minimal of man-hours. Automation built on a huge population of plants allows the use of Machine Learning (ML) and Artificial Intelligence (AI) algorithms to continuously improve detection capabilities.

The shortcomings of the traditional focus on standard rating conditions have been discussed in the industry for a long time. Independent of each other, the IOR in the UK and the German Engineering Association (VDMA) initiated evaluation of an efficiency-based approach for design many years ago, so as to improve system efficiency measurement. In a project managed by the Research Institute of Sweden (RISE), including representation from VDMA, IOR and ClimaCheck, the System Efficiency Index approach was adapted for visualisation of field measurements. This work was presented in 2014 (Lane Anna-Lena, 2014) and has been applied since then in the performance analysis of thousands of HVACR-systems.

The Dashboard below (Figure 2) visualises the KPIs for a near state-of-the-art water-cooled chiller. The Dashboard visualises all the values required for a detailed Service Report that confirms the performance of all components in the process (compressor/evaporator/condenser) and whether or not the refrigerant charge is correct and if the expansion device is functioning as it should. This includes all the traditional information such as the values for subcooling, superheat, temperature approaches and secondary flow rates, but also adds the individual component efficiencies.

In Figure 2 below, the System Efficiency Index (SEI) of 45% to the left shows that this high efficiency chiller is performing near state-of-the-art for a water chiller/heat pump. The COP (Cool) is 6.96, but without referencing this to the operating conditions, this COP value contains limited information for proper evaluation, as it will alter significantly with changes in the chilled and condensing water temperatures. The Refrigerant Cycle efficiency in this chiller example is high, since the chiller is equipped with an economiser. The isentropic efficiency of the compressor is within a few percentage points of a state-of-the-art machine and the condenser and evaporator are operating with high efficiency.

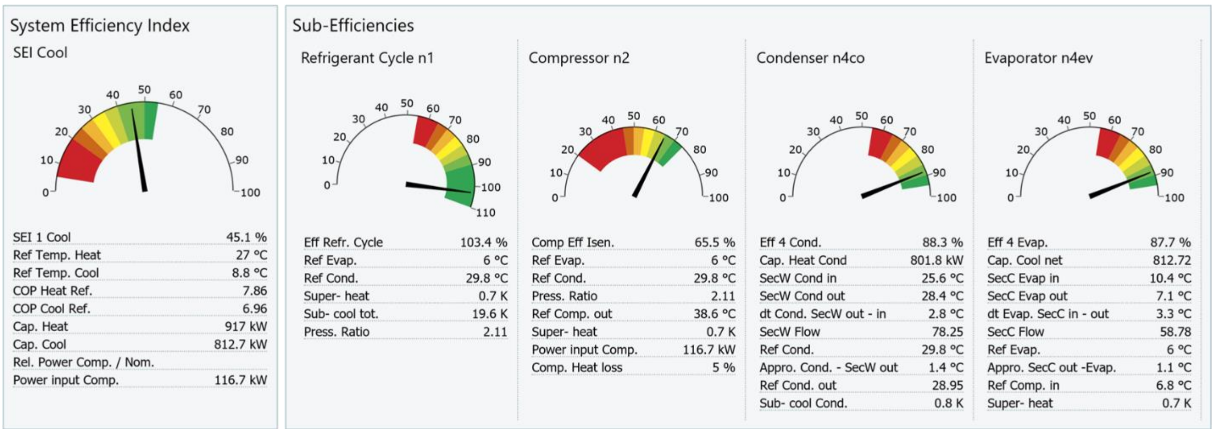

Figure 2. A high efficiency chiller with COP 6.96 this is operating with economiser offering a high cycle efficiency

An SEI of 45% indicates a very efficient refrigeration process and this is a far more reliable benchmark than just the COP (Cool) of 6.96, as this will decrease significantly with increasing outdoor/decreasing chilled water temperatures, even though the chiller is still in excellent condition. The efficiency perspective offers an effective way to detect any deviations in component or overall system performance, long before this causes a compressor or system failure and the excessively higher energy consumption that will occur leading up to the point of failure.

4.1. The benefits of using SEI and sub-efficiencies as benchmarking KPIs versus COP

The three examples below show different operating modes for the same heat pump to highlight the importance of understanding the limitations when relying on COP as a benchmark, or trouble shooting parameter. This is a grounds source system operating as a heat pump during winter and as a chiller in summer (when free cooling is not sufficient). This system operates over a wide range of temperatures and capacity levels, as most systems should do. One of the major optimisation potentials is to ensure that the temperature lift is minimised. In Figure 3, the heat pump operates at high supply water out of the condenser, resulting in a COP (Heat) of 2.9 and a SEI of 35%. (SEI is achieved by dividing the measured COP with the Carnot COP of the reference temperatures that in this case, is the mean of water return and supply temperatures in the condenser and the mean value of return and supply temperatures of the ethanol solution in the evaporator). In Figure 4, the same heat pump is operating at lower return water to the condenser, which results in a COP (Heat) of 4.1, which represents a 41% lower energy consumption per kWh heating, with almost exactly the same efficiency of the heat pump as shown by the SEI of 35%. In Figure 5, the COP is 2.98, but the SEI has decreased to 30% due to the reduction of the compressor efficiency, when the screw compressor is off-loaded with the slide valve regulation.

Attempting to visualise COP as a KPI is challenging, if not compared at rated conditions, and these may never occur at a particular site. To maintain a constant COP would be very inefficient, as only one condition would be maintained and only be the worst case, when a high temperature lift is required to deliver the specified comfort level.

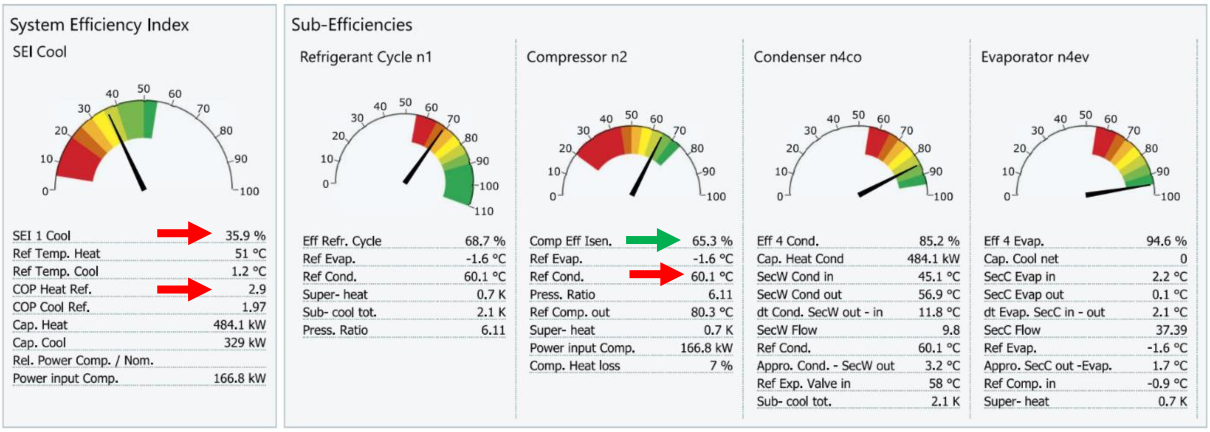

Figure 3. Ground source heat pump operating with full capacity at high temperatures in heating system reaching a COP heating of 2.9

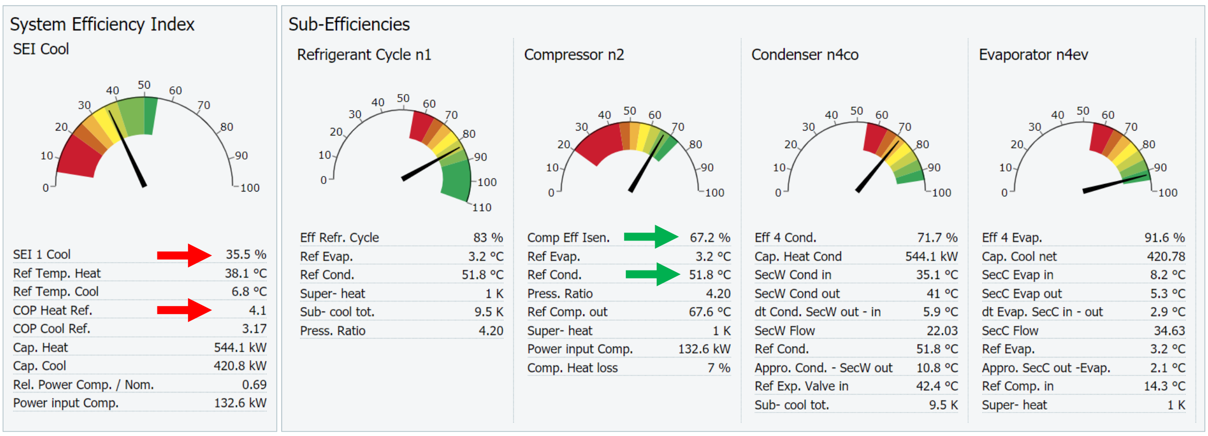

Figure 4. Same heat pump at lower temperatures in heating system reaching COP of 4.1 this is 41% better COP than operating conditions above but system is as efficient (35%) as shown by the SEI

Whereas when the same heat pump is offloading the screw compressor the performance decrease

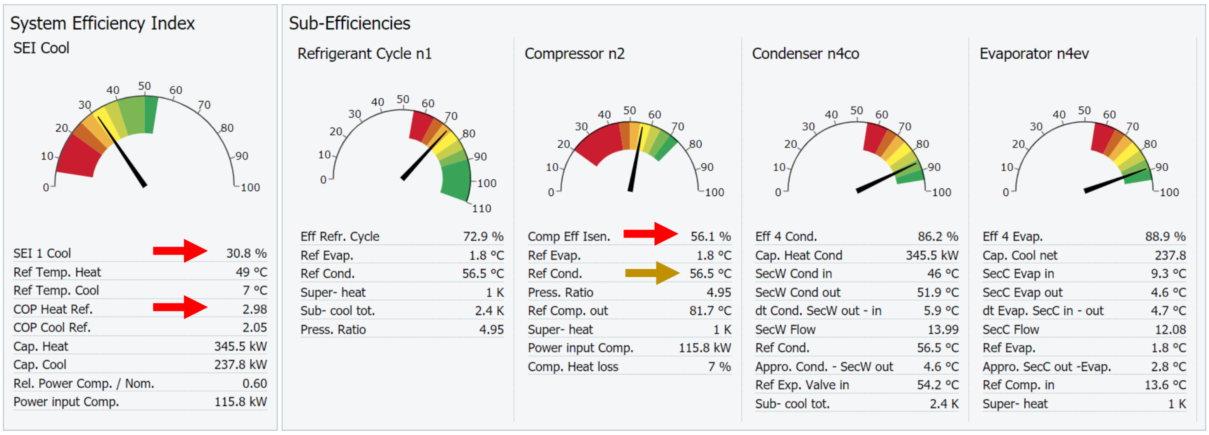

Figure 5. Same heat pump at part load - reducing screw compressor efficiency to reduce COP heat to 2.98 the reduction of compressor efficiency also has a direct impact on SEI that is reduced to 30.8%

SPF/SCOP will be the result of variations in operating conditions affected both by factors that can be affected by commissioning, operation and control, and those that cannot. A flow-based energy meter and an electrical power meter registering a SPF/SCOP will not provide sufficient information to improve the system or to define the cause, if there is deviation from design specifications.

Significant energy savings are achievable and failure rates can drastically be reduced with a well-planned M&V strategy that is focused on making detailed information available to experts, with access to automated analytics based on a huge database. Early detection of any deviation in efficiencies on a component level, as well as deviation in the energy signature, will pinpoint issues when they occur and remove the accumulation of urgent engineer call-outs during heat waves and cold-spells. Predictive maintenance will change the industry and move the focus to optimisation and avoidance of faults, rather than callouts to repair/replace failed components. It is obvious that there will be faults that cannot be prevented, as they occur without warning, but these are very few and the number of sites where poor operation causes high energy bills and unnecessary failures, is huge. Most compressor failures could have been detected months or years before they occur and thus prevented.

5. THE DEVIL IS IN THE DETAIL OF OPERATION

The above shows the complexity in understanding performance when analysing dynamic systems. These consist of a number of sub-systems and many controls and all must interact in the best way in order to deliver good performance and reliability. Experience shows that there are so many possible inefficiencies in a modern system, that it is impossible to cover these in this paper. There are hundreds of components such that each might cause a system to operate less efficiently, and that the only cost-effective way is to start from the heart of the system, establish properly how it is working and then work through the system to identify the cause of inefficiencies. The achievement of good comfort or food being maintained at the desired temperature is not good enough. We also have to ensure and verify that the water chiller/heat pump/refrigeration system works efficiently and reliably. Below, the impact on the energy consumption of leaving a fan controller in the default position is shown. This is a result of the sensitivity of an increased temperature lift. It is still common that we see air-cooled water chillers and water-cooled chillers with dry coolers left to operate at default or design settings, thus forcing condensing temperature to 35-45°C. The case below in **Error! Reference source not found.** shows how a fan controller increases condensing temperature and pressure - drastically reducing the System Efficiency Index to 17% and increasing the wear as pressure ratio is much higher than necessary. It should be noted that the COP (Cool) is 3.81, which may not look bad, until the low ambient operating condition is understood. The performance envelope for this particular compressor allows a condensing temperature of 30°C for these conditions. The decrease of condensing temperature to 10K with an increase in COP to 4.99 represents an energy saving of 30% and we are still limiting system performance to stay within the compressor operating envelope and reducing wear on compressor.

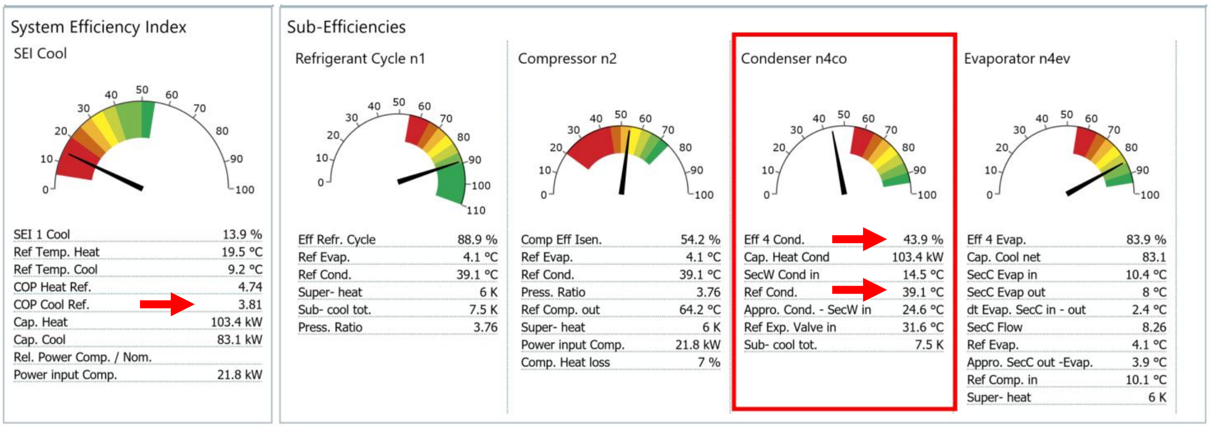

Figure 6. Air-cooled chiller operating at low ambient conditions condensing at 39°C due to default setting of fan controller

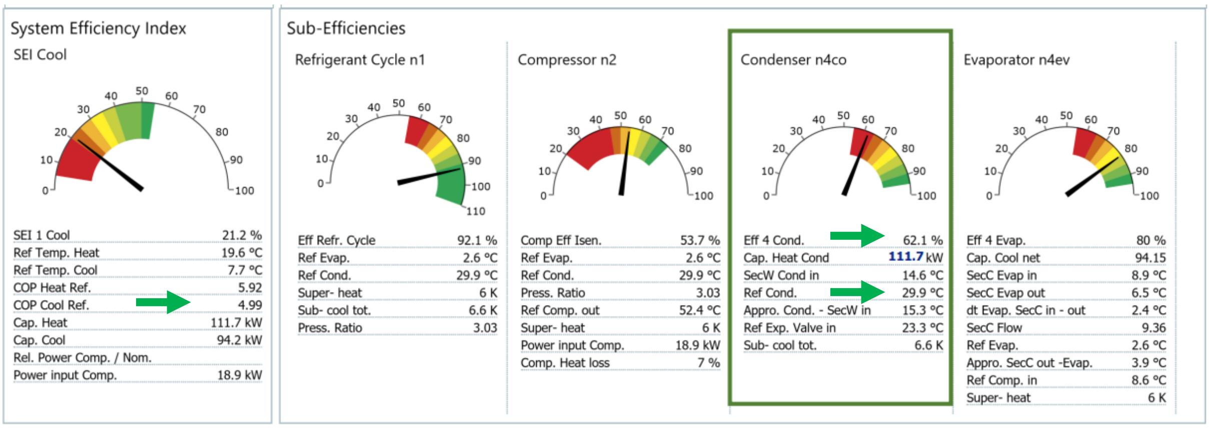

Figure 7. Performance of the air-cooled chiller after adjusted fan control efficiency has increased with 30%

The graph in Figure 8 show a water chiller with an unstable capacity control over most of its operating time. These problems are common and often go undetected, as during the scheduled maintenance work, equipment is forced to run by changing controller set points or by manual override operation, as it is desirable to have stable system operation at the time of the inspection. Time constraints compel the engineer to avoid waiting until a system starts or having the risk of it stopping during inspection. Unstable operation most often occurs at low load conditions.

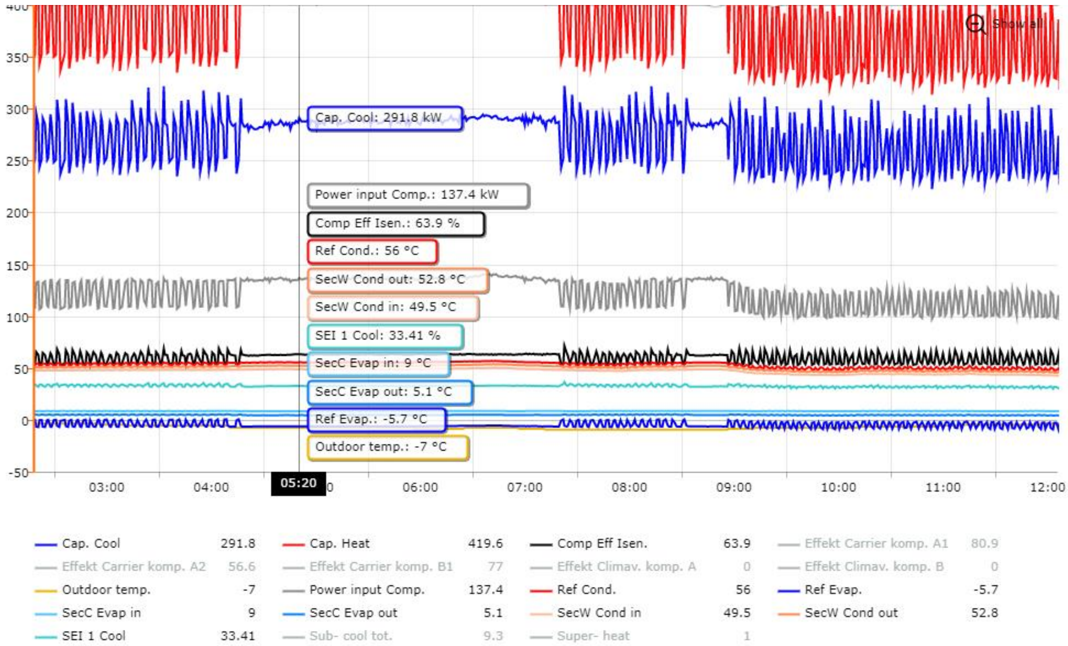

Figure 8. Capacity control that is unstable during a majority of the time of operation shown – Grey is power, blue cooling capacity and res heating capacity

In the worst-case, poor capacity control results in the operation shown in Figure 9, where the compressor at certain load conditions, starts and runs for only a minute or less. This causes significant wear on the compressor and often results in problems with oil return. Oil will leave a compressor at start up and run time is not sufficient to ensure adequate oil return to the compressor. Oil will accumulate in the evaporator until the compressor stops via its oil protection system or instead, fails. Predictive maintenance include identification of these issues during operation, as these will result in failures and alarms if the problems are not addressed.

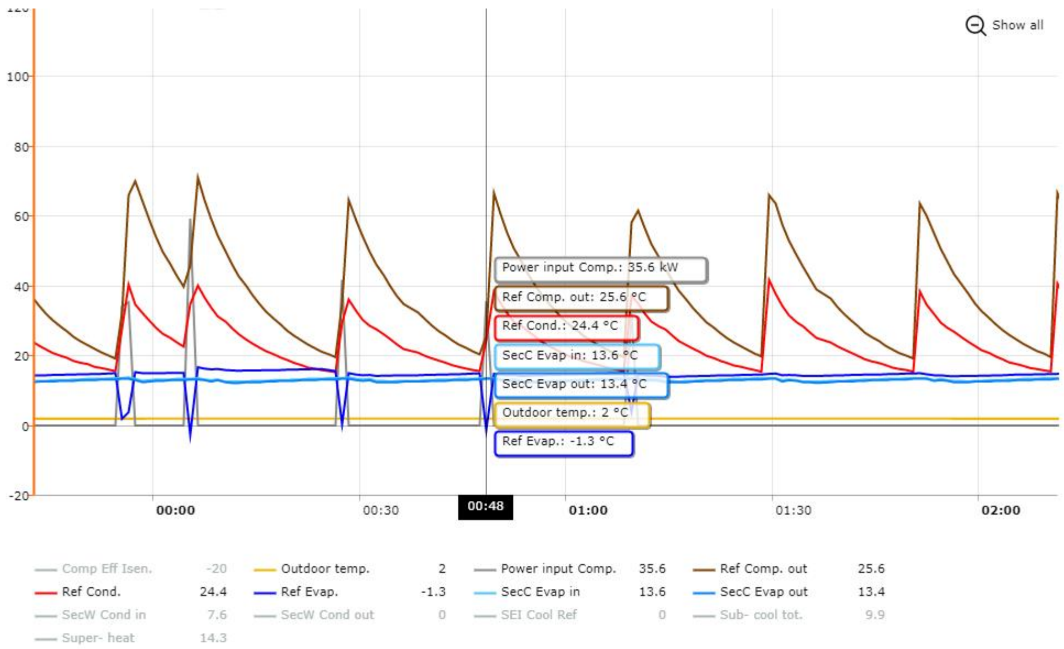

Figure 9. Example of chiller running on ten minutes restart protection

Figure 10 shows an example of an unexpected problem that can be picked up by predictive maintenance based on performance analysis (*I have only seen this at this site, in spite of long experience in monitoring and troubleshooting*). At 18:50 in the graph below, the condensing pressure suddenly drops to the evaporation pressure as the off-loaded start mechanism is activated. This had been missed by the conventional BMS and maintenance practice. The compressor consumes 25 kW electrical power, but does not generate any cooling capacity. It can be seen that discharge temperature is higher than when the chiller is producing cooling earlier in the afternoon. If not identified by monitoring, this operation would result in high risk of compressor failure as lubrication and cooling are not designed for this type of continuous operation in off-loaded mode.

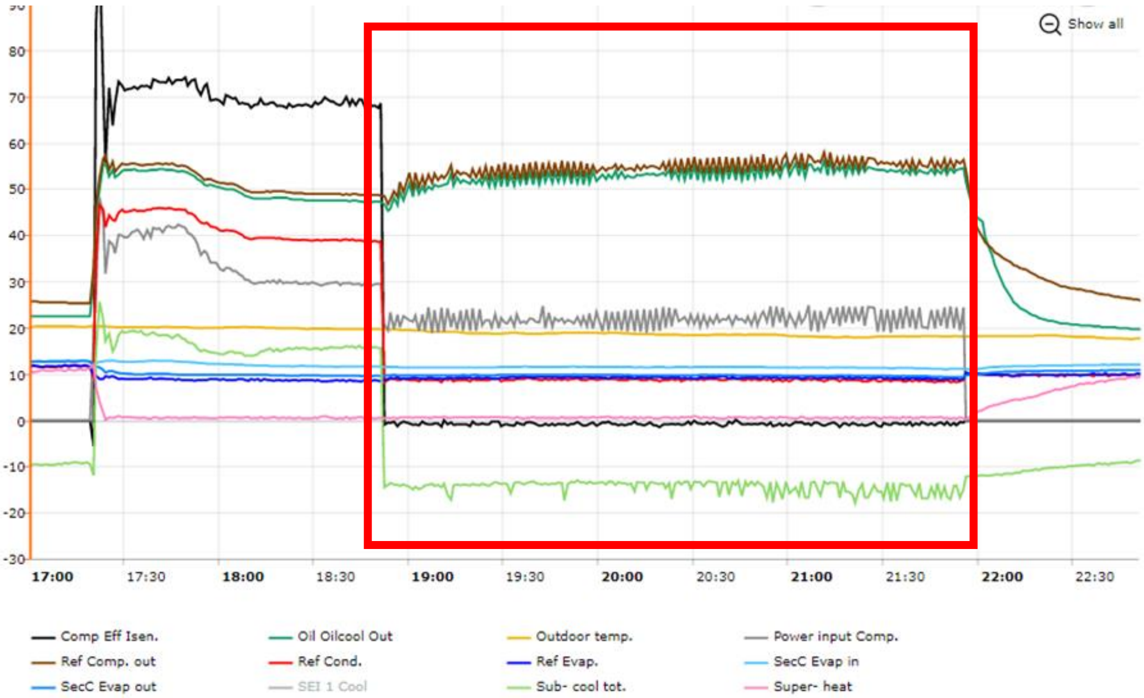

Figure 10. Chiller is in the red box operating 3 hours without pressure increase due to the mechanism for unloaded start being activated. During this time no cooling capacity is generated and there is significant risk for damage

6. CONCLUSIONS

The complexity of HVACR systems highlights the value of using the capabilities of web-based performance analysis for predictive maintenance. Thermodynamic performance analysis can be combined with modern automation tools to identify deviations in efficiency at a component level and if any parameter is moving outside of an allowable range. Experience from thousands of systems and the problems identified can be used for early detection. Continuous improvement of fault detection and diagnosis is not achievable in local BMS solutions, unless these are integrated within web-based analytics. Cloud-based analysis allows “experts” to build experience through on-line monitoring and the troubleshooting as they build experience from a large population of systems and can support local staff to prevent failures. For the maintenance technicians/engineers, the web-based information totally changes the data they have available for trouble shooting and optimisation, as they can scroll back and forth in time and identify how performance changed, with the level of detail normally only possible from a laboratory Test Rig.

Early warnings can be triggered for any deviation, bringing these events to the attention of an assigned receiver long before anyone at the site experiences the effects or get a local BMS alarms. Most problems can be pinpointed long before they are noticed at the site and corrective measures can be planned in time. Any deviation in compressor, condenser or evaporator performance can be identified when it occurs. To know if the cause is flow rate, heat transfer, refrigerant charge or expansion device issues or the very common control issues saves time and money. The right person can go to site with the appropriate tools and spares. As detection of issues takes place when a problem first occurs, long before failures, corrective measures can be planned, when most convenient for all involved, which is why predictive maintenance is so cost-effective. As equipment owners are increasing their focus on sustainability, cost-effective operation and increasingly also require documentation of the performance, those that do not upgrade their competence and services will lose such customers. With an energy saving potential of 10-30%, reduced failure rates and the limited cost of implementation - **predictive maintenance based on performance analysis is the future.**

REFERENCES

Berglof. (2005). *Methods and Potential for on-site Performance Validation of Air Conditioning.* Las Vegas: IEA.

Fahlén, P. (1989). *Capacity measurements on heat pumps - A simplified measuring method.* Swedish Counsil for Building Research.

IEA. (2021, March 6). *Annex 52.* Retrieved from https://heatpumpingtechnologies.org: https://heatpumpingtechnologies.org/annex52/

Lane Anna-Lena, B. J. (2014). *Method and guidelines to establish System Efficiency Index during field measurements on air conditioning and heat pump systems.* Borås, Sweden: SP, Technical Research Institute of Sweden.