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Reduction of Carbon Emissions of HVAC Systems: A Case Study of a Pharmaceutical Site in France

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Abstract Heating, ventilation and air conditioning systems (HVAC) are widely present in industry. They permit to maintain strict environmental conditions such as in clean room in pharmaceutical and aerospace industries. They also permit to maintain personal health and comfort (e.g., in offices). This article is a case study in an industrial pharmaceutical site in France. HVAC systems represent 57% of site's carbon emissions because air must be transported and undergo several different treatments: heating, cooling, dehumidification, and Filtration. Moreover, those systems are generally overdesigned, operate very far to the specification limits and/or regulation are not optimized. To minimize carbon emissions, a specific methodology has been developed for ensuring to make the right choices when implementing a new HVAC or modifying an existing one. This methodology contains 4 steps: reduce quantity of air, reduce air treatment periods, efficient air treatment by design and efficient air treatment by management. Each step includes complex, simple and innovative actions such as electronically commutated motor in place of conventional motor. The methodology developed does not degrade global performance and thermal efficiency of systems and answer to quality, environment, health, and safety requirements. The application of this methodology has permitted to reduce carbon emissions of HVAC systems by 24% in less than 3 years.

Keywords Carbon emissions reduction, HVAC, Methodology, Best practices, Energy efficiency

1. Introduction

Energy efficiency is one of the levers to reach carbon emissions reduction. Renewable energy is an example of other levers. Energy efficiency contains different parts: Material and equipment efficiency (i.e., with the highest energy efficiency rating), energy modelling/optimization (i.e., disclose unseen energy efficiency through powerful algorithms [1,2]), energy planning [3] etc.

A combination of at least two of those parts help greatly to achieve carbon reduction goals and that's the approach and contribution of this paper.

For reaching energy efficiency, it is key to start by a deep dive analysis of each high consuming equipment/process [4]. In this case study, it has been done during energy audits. Heating, ventilation, and air conditioning (HVAC) systems are generally among the high consuming equipment. "The growing reliance on HVAC systems in residential commercial and industrial environments has resulted in a huge increase in energy usage, particularly in the summers months" [5].

The way an HVAC is designed and used has a high impact on its energy consumption and therefore on its carbon emissions.

This paper adds to the literature on HVAC carbon emissions reduction a specific four steps methodology combined to complex, simple and innovative actions.

During this case study, the thermal efficiency and the performance of all HVAC have not declined. Indeed, less energy is used but always for the same effects (same temperature, same humidity etc.). For quality critical HVAC systems, validations have been done through a robust validation process (installation qualification, operational qualification, and performance qualification).

2. HVAC Principle of Functioning (Temperature, Pressure and Hygrometry Regulation)

All HVAC in this case study contains as a minimum the following elements:

- A sound trap: It reduces the noise generated by the installation and the air circulation.
- A filter: Its role is to stop the particles circulating in the air.
- A fan: It ensures the continuous flow of air in the distribution and return networks.

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- A control flap: It is used to regulate the air flow.
- A dehydrator: It has the function of dehydrating part of the air as needed. The other part is bypassed.
- A bypass: It allows part of the air not to be treated by an element of the plant (e.g., the dehydrator).
- A cold coil: The function of a cold coil is to cool and dehumidify the air.
- A hot coil: It is used to heat the air.

Figure 1 represents a typical HVAC on the industrial site.

Figure 1. Overview of a typical HVAC of the case study

Figure 2 includes pictures of same major elements.

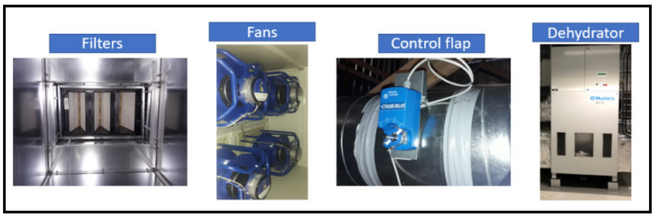


Figure 2. Pictures of different HVAC elements

Table 1. Electrical Consumption per Equipment/Process for 2018

Equipment/Process	**2018 consumptions (kWh)**
Compressed air	624 138
HVAC dehumidifiers	991 858
HVAC motors	2 494 617
Dust collectors	431 293
Hot water production	190 626
Chilled water production	1 608 581
Purified water	161 821
Lighting and sockets	708 608
Industrial ovens	14 148
Information Technology rooms (uninterruptible power supply and HVAC)	627 220
Warehouses (chargers, lighting, various)	99 150
Vacuum pumps	76 363
Process	635 399
Coating equipment	423 428
Kitchen	148 223
Fire extinction system	16 324
Site total consumption	**9 251 797**

3. Site Electrical Consumptions

Several equipment on site use electricity. The electricity is supplied by four transformers (three 1250 kVA oil transformers and one 630 kVA dry transformers).

Total site electrical consumption for 2018 is 9 251 797 kWh before application of the HVAC carbon emissions reduction methodology. Actions have been started beginning of 2019.

Table 1 contains electrical consumptions of all equipment/process during 2018 (the reference year).

As shown in figure 3, HVAC consumptions (motors, dehumidifiers (DSH) equipment and chilled water mainly) represent 57% of site electrical consumption.

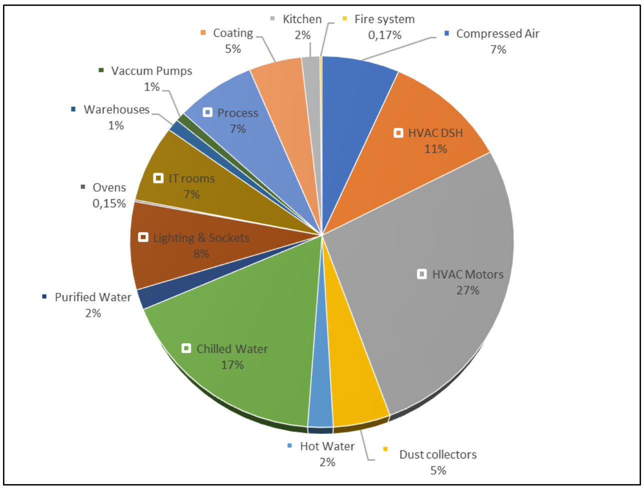


Figure 3. 2018 site's electrical consumption repartition in %

The coefficient "CO2 emissions per kWh of electricity" used in this case study is 0,069 and it has been applied to all years for allowing an accurate comparison.

After applying the CO2 coefficient, site has emitted 638 tons of CO2 emissions (electricity consumption) and 242 tons of CO2 have been emitted because of HVAC.

4. HVAC Electrical Consumptions & CO2 Emissions

HVAC motors are the highest electrical consumers (27% of site's electrical consumption). Therefore, it is important to know consumption of each system. Table 2 summarises those consumptions.

As site's dehumidifiers are high consuming equipment (11% of site's electrical consumption), they have all been fitted with electrical meters. Table 3 includes electrical consumption and CO2 emissions of each dehumidifier of HVAC and air fresh unit (AFU) during 2018.

Table 2. Electrical Consumption of all HVAC Motors in 2018

HVAC names “Motors”	Areas covered	2018 Elec. cons. (kWh)	2018 CO2 (kg)
HVAC 22	Packaging line	177 933	12 277
HVAC 14	Warehouse	47 854	3 302
HVAC 16	Laboratory	101 404	6 997
HVAC 15	Warehouse	54 016	3 727
HVAC 17	Offices	9 877	682
HVAC 30	Packaging line	46 490	3 208
Heat Pumps	Warehouses	5 526	381
HVAC 20 & 23	Offices/Laboratory	14 487	1 000
HVAC 11A	Manufacturing	43 403	2 995
HVAC 11B	Manufacturing	38 944	2 687
HVAC 26	Manufacturing	43 473	3 000
HVAC 25	Corridor in manufacturing	52 545	3 626
HVAC 3B	Manufacturing	27 387	1 890
HVAC 21	Manufacturing	58 988	4 070
HVAC 27	Manufacturing	89 561	6 180
HVAC 29	Airlocks in manuf.	34 280	2 365
HVAC 09	Packaging & offices	10 768	743
HVAC 32	Manufacturing	38 021	2 623
HVAC Laboratory	Laboratory	13 693	945
HVAC 6B (with DSH)	3 packaging lines	210 543	14 527
HVAC 28	Laboratory	23 740	1 638
HVAC 31	Packaging corridors	70 260	4 848
HVAC 13B	Laboratory	40	3
HVAC 12A / 12B / 13	Offices/Changing rooms/Laboratory	223 007	15 387
HVAC 04	Warehouse in manufacturing	165 603	11 427
HVAC 10	Airlock for articles	46 366	3 199
HVAC 11C	Washing room	19 801	1 366
HVAC 05	Manufacturing	133 292	9 197
HVAC 07	Packaging line	47 291	3 263
HVAC 06	5 Packaging lines	260 667	17 986
HVAC 01	Manufacturing	181 556	12 527
HVAC 08	Secondary Packaging (all lines)	186 818	12 890
HVAC 02	Admin. offices	9 080	627
HVAC 03	Admin. offices and restaurant	7 903	545

Table 3. Electrical Consumption of all Site’s Dehumidifiers in 2018

HVAC names “DSH”	Areas covered	2018 Electricity consumptions (kWh)	2018 CO2 Emissions (kg)
DSH 11A	Manufacturing room	36 458	2 516
DSH 11B	Manufacturing room	13 874	957
AFU S1 / DSH1	Manufacturing room	365 804	25 240
AFU S2 / DSH2	Manufacturing room	161 579	11 149
DSH 28	Laboratory	39 009	2 692
DSH 07	Packaging line	99 237	6 847
DSH 06	5 Packaging lines	210 086	14 496
DSH 01	Manufacturing room	65 811	4 541

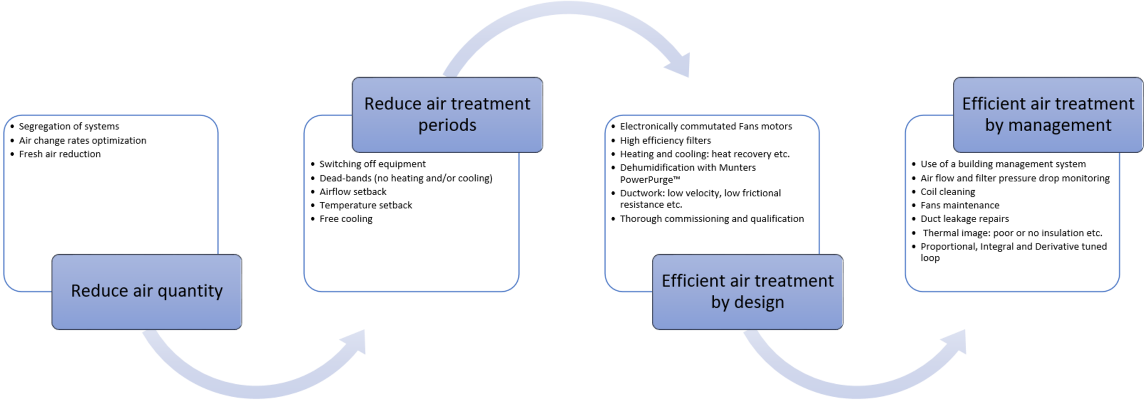


Figure 4. Flowchart of HVAC research methodology

5. Methodology

The methodology used in this case study to reduce the consumption of each HVAC is the following:

- 1st step = Reduce quantity of air
    - Goal is to reduce as much as possible the quantity of air to be treated while respecting all the requirements of the area to be treated (e.g., avoid cross contamination between area).
- 2nd step = Reduce air treatment periods
    - After deep analysis air treatment can be minimized in some situation.
- 3rd step = Efficient air treatment by design
    - This step consists of maximizing the efficiency of the air treatment thanks to an adapted design.
- 4th step = Efficient air treatment by management
    - This last step is to define and put in place a high-level management during the whole life of the HVAC (e.g., continuous monitoring with a building monitoring system).

Figure 4 represents the methodology defined and applied and the associated actions.

6. First Step: Reduce Quantity of Air

6.1. Air Changes Rates

An air equipment is often overdesigned to attain the requirement in the user requirement specification (e.g., because of quality requirement). Air change rates (ACR) can be reduced in most of the cases while maintaining the environmental conditions (e.g., for product protection).

ACR are influenced by:

- Initial design conditions
- Heat gains in the room
- Containment between rooms (pressurization)
- Make up air for local extract

A good air distribution will also allow colder/heater air to be delivered in smaller quantities for same cooling/heating effect.

It is important to exclude fixed large equipment such as vessels from room volume to calculate air change per hour.

"The Fan Affinity Law (physics) states that the power used by a fan motor is reduced exponentially as the speed is reduced" [6].

In figure 5, we can observe that:

- 20% reduction in fan speed = 47% reduction in power
- 50% reduction in fan speed = 87% reduction in power

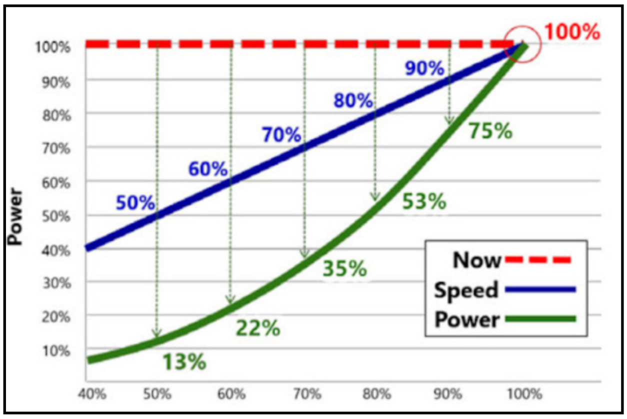


Figure 5. Affinity fan laws: Power and Air Flow [6]

The power required to move air through the fan or system varies with the cube of the change in volume and is calculated as follows:

$$W2 = (V2/V1)^3 \times W1 \quad (1)$$

W2 = New power input (Watts)
W1 = Power input (Watts)
V1 = Volume of air (m^3/h)
V2 = New volume of air (m^3/h)

This is the reason ACR reduction is such an effective energy reduction strategy. Always install variable frequency drives [7] on supply and extract fans to vary volume and air change rate to need and to also allow pressure control. Air handling units and fans should also be located as close as practicable to the point of delivery to minimize energy dissipation and pressure loss in supply and extract ducts. Heat gains from large equipment (such as refrigeration/ freezer cabinets) should be mitigated by direct extract, rather than active cooling and ventilation wherever possible.

In this case study, ACR of HVAC 4, 8 and 6 have been modified. See results in section 10.

6.2. Fresh Air Reduction

Fresh air is required for occupant health and for pressurization. For each area, the air fresh air rate is analysed. The aim is to recycle as much as possible the extracted air because it has been already treated.

The following element have been considering in reducing fresh air:

- Possible pressure cascade losses
- Room leakage
- Duct leakage
- Exhausted air through dust extract

In this case study, fresh air reduction has been applied to HVAC 6. See results in section 10.

6.3. Segregation of Systems

Implementation of separate air supply systems for areas with different requirements to:

- Minimize local re-heat for areas with different temperature requirements
- Enable air supply systems to intermittently occupied areas to be switched off or reduced (subject to area classification)
- Minimize pressure drops from excessively long or complex distribution ducts

In this case study, segregation of systems has been applied to HVAC 6. See results in section 10.

7. Second Step: Reduce Air Treatment Periods

7.1. Setpoints and Dead-bands (Temperature/Relative Humidity)

The principle is to ensure appropriate dead-bands (or offsets) for heating and cooling [8,9]. For reaching that, single setpoint values must be avoided. This will help eliminate unnecessary simultaneous heating and cooling as shown in figure 6.

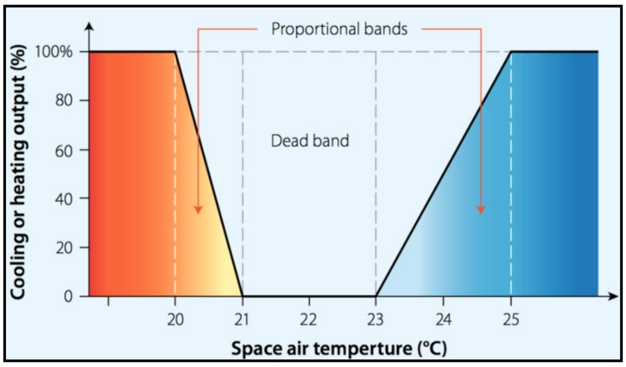


Figure 6. Typical energy efficiency temperature set point and control bands [10]

Most of time, very tight temperature or humidity control is not really required (e.g., for product quality). A typical room range of 19-23° and 30-60% RH (Relative Humidity) would be acceptable for people comfort (but need to consider gowning requirements).

In this case study, multiple setpoints and dead-bands have been applied to HVAC 4, 8 and 6.

7.2. Temperature Setback

When rooms are occupied, it is best to have a dead-band control in operation. However, when rooms are unoccupied or not in use a setback can be introduced.

Temperature setback is place for nearly 8 years on several HVAC. This action is indicated in this case study for information.

As seen in figure 7, this setback widens the dead-band and therefore reduce the demands on the HVAC systems.

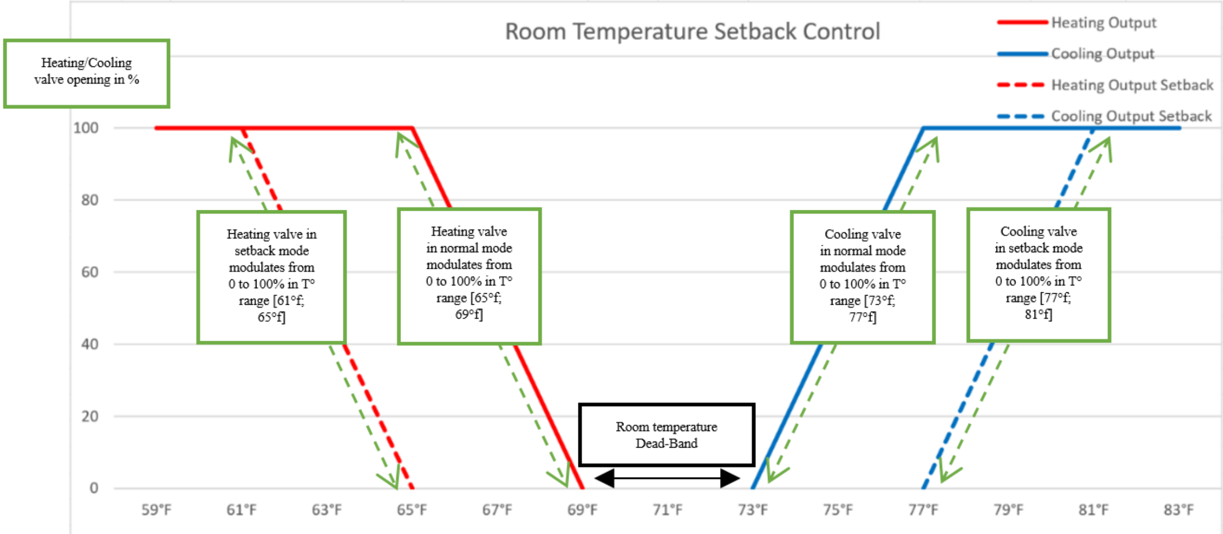


Figure 7. Room temperature setback control

7.3. Airflow Setback

Switching off equipment when not in use is the best energy savings (demand based). Airflow setback is widely deployed in non-critical areas such as administrative areas and cafeterias.

Airflow setback can be deployed in production areas when not in use (outside shifts). Nevertheless, it is important to maintain room pressurization where required.

Airflow in laboratories is setback during out of working hours but maintain temperatures and relative humidity within limits and maintain a negative pressure where required.

A building monitoring system is used for managing setback mode of all equipment. This tool can realize complex sequence of operations.

Every week before the new week coming, a quick meeting is set between utilities service in charge of HVAC and production planning service for sharing opening of production areas (for then setting HVAC hours of setback in the building monitoring system).

Airflow setback is place for nearly 8 years on several HVAC. This action is indicated in this case study for information.

7.4. Free Cooling

When conditions are favourable (outside air temperature is below return air temperature), the outdoor air damper is the first stage of cooling [11].

During the spring and fall seasons especially, the opportunity to use outdoor air to provide free cooling saves energy while also boosting indoor air quality. To accomplish this sequence air handling unit are equipped with modulating return and outdoor air dampers. Temperature (or enthalpy) sensors are also in place for allowing the building monitoring system to determine which type of air is most appropriate for cooling (outside air for free cooling or return air for mechanical cooling).

Free cooling is place in place on many HVAC. This action is indicated in this case study for information.

8. Third Step: Efficient Air Treatment by Design

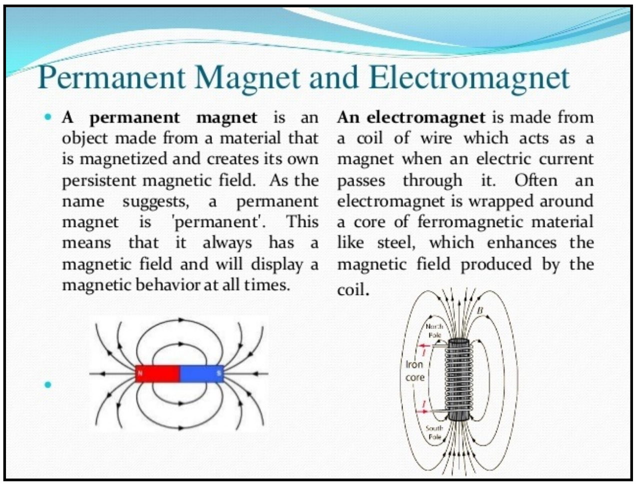
Overdesign must be avoided in designing HVAC systems and an optimization of HVAC systems design is the solution to reach that objective [12].

8.1. Motors and Fans Specifications

Fans design should be of the highest efficiency available (technology is advancing quickly). Therefore, the fan is selected to provide maximum efficiency at the actual air flow required, or the most frequent air flow for fans that will operates across a range of airflows. Fans are fitted with backward curved blades. Fan walls consisting of multiple fans are considered in place of large single fans to improve efficiency part load efficiency. Fans are also direct driven with high efficiency motors.

All motors are high efficiency Electronically Commutated (EC) motors [13]. An EC motor has the following key attributes:

- Brushless Direct Current (DC) motor (rotor and stator)
- A permanent magnetic rotor (see technical differences with electromagnet rotor in figure 8)
- Alternative Current (AC) is converted to Direct Current (DC) by electronics commutation
- An Electronic card modulates the speed of the DC motor



Permanent Magnet and Electromagnet

- **A permanent magnet** is an object made from a material that is magnetized and creates its own persistent magnetic field. As the name suggests, a permanent magnet is 'permanent'. This means that it always has a magnetic field and will display a magnetic behavior at all times.

An electromagnet is made from a coil of wire which acts as a magnet when an electric current passes through it. Often an electromagnet is wrapped around a core of ferromagnetic material like steel, which enhances the magnetic field produced by the coil.

Figure 8. Differences between permanent magnet and electromagnet [14]

As represented in figure 9, for the speed range 50%-100%, the efficiency of an EC Motor is between 91-92% whereas for an AC Motor it is between 84-89% [15].

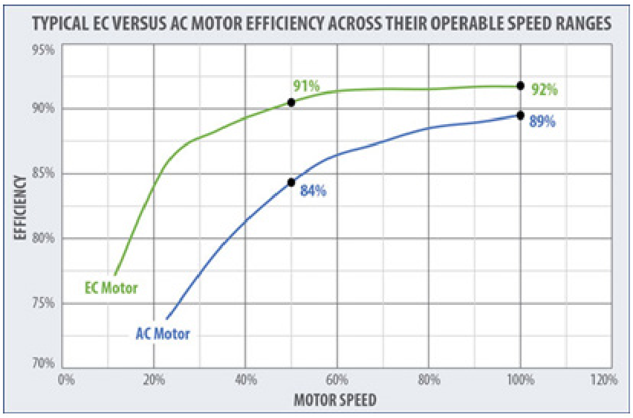


Figure 9. Typical EC Versus AC Motor Efficiency across operable speed ranges [16]

Main benefits of EC Fans are at reduced air flows. Indeed, AC Fans cannot be reduced below 20-25% of its nominal power on the contrary of EC Fans as shown in figure 10.

Therefore, EC Fans save more energy than AC fans at reduced air flows and can be reduced to 5-10% of its nominal power (especially when in fan grid arrangement).

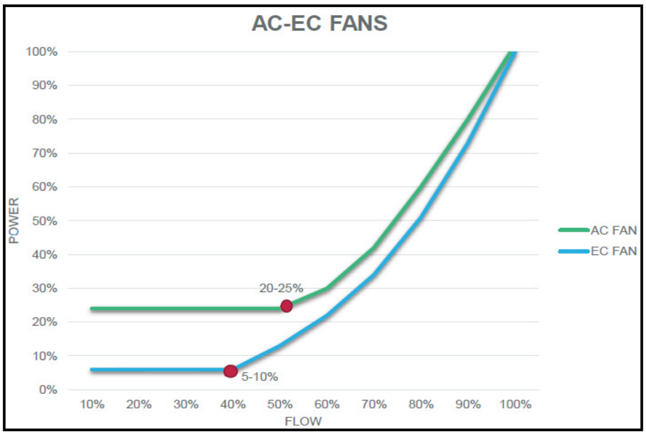


Figure 10. AC Fans vs EC Fans

There are different types of AC fan motor configuration = Belt drive AC centrifugal cased fan; Direct drive AC centrifugal cased fan; Direct drive AC centrifugal tubular or plug fan.

They can be changed by different types of EC Fan motor configuration: Single cased centrifugal fans with EC motor; Single plug centrifugal fan with EC motor; Multiple plug centrifugal fans with EC motor – Fan Array.

In this case study, all AC fan motor have been replaced by multiple plug centrifugal fans with EC motor as in figure 11.

Figure 11. Example of direct drive multi grid fans with EC motors installed

Advantages:

- Efficiency level up to 90%, which is substantially higher than the 70-80% achieved by AC motors.
- High efficiency at nominal and reduced airflows (setback mode)
- No lower speed limitation compared to variable speed drive on single fan
- Increasing the overall efficiency of an application
- Longer life cycle of the system
- Infinitely variable control (speed can always be adapted to the requirements)
- Reduced noise levels
- The EC Fans do not require inverter or speed controller
- It improves system redundancy (fan grid system)
- It reduces maintenance costs (smaller fan sizes, easy to handle and replace and same fan modules) and particularly in fan grid system

Limitation:

- Limited system static pressure to 2000 Pa

In this case study, motors, and fans of HVAC 4, 6 and 8 have been changed. See results in section 10.

8.2. Filters

Filters are keys element in HVAC [16]. They are used in industrial, commercial, and residential HVAC applications.

A filter spends on average 1700 kWh/year. For example, it is:

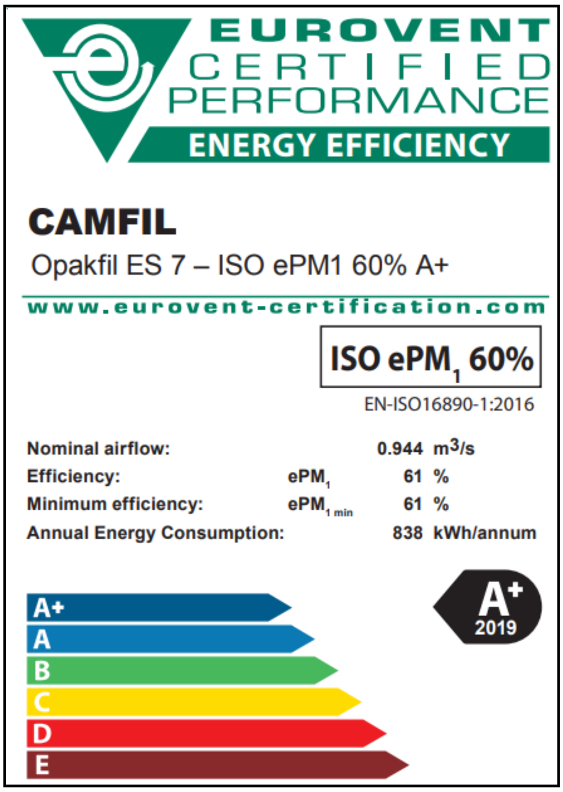
- 3 times more than a dryer,
- 5 times more than a class A refrigerator,
- 13 times more than an iron, ...

It should also be remembered that a high efficiency filter will certainly create good air quality, but also pressure drops synonymous with energy expenditure.

It is necessary to conduct a global, energetic, and environmental reflection. It is possible to save energy but not at the expense of filtration efficiency. The ventilation and associated equipment of a building represent up to 70% of its overall energy consumption and are often overlooked.

The filtration strategy in this case study is the following:

- Maintain/improve current filtration air quality
- Change to low energy filtration
- Remove low-capacity panel filter
- Consider removing panel filters and just having bag filters large capacity
- Add pressure/volume control



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Nominal airflow:		0.944	m^3/s
Efficiency:	ePM_1	61	%
Minimum efficiency:	$ePM_{1\ min}$	61	%
Annual Energy Consumption:		838	kWh/annum

Figure 12. Example of filters energy efficiency labelling

Energy classification and standard EN779: 2012

Eurovent's energy efficiency classification represents a powerful tool [17], as it allows to know the class of annual energy consumption. Today, all Eurovent member air filter suppliers must affix an energy label (as illustrated in figure 12) on each filter box, rated from A (lowest energy consumption, between 0 and 1200 kWh/year) to G (the highest).

For any new HVAC or HVAC modification, this classification is used when selecting filters.

In this case study, high efficiency filters have been put in place in HVAC 6 (HVAC 33 and 34 now).

8.3. Heating and Cooling

8.3.1. Heat Recovery

Heat recovered from exhaust air is used to pre-heat fresh air when there is enough temperature or enthalpy difference between supply air and exhaust air streams [18]. This requires supply air and extract air fans to be in the same location.

Thermal wheels are the first option. "The overall efficiency of rotary wheel heat recovery is generally much higher than that of any other air-side heat recovery system due to the nature of the heat wheels, which allow heat to transfer from the exhaust stream to the supply stream without having to pass directly through the exchange medium" [19].

Plate heat exchangers or heat pipe recovery systems are used where thermal wheels cannot be used.

Bypass arrangements are used in installations where required by seasonal climatic conditions.

By setting higher discharge air temperatures when demand for cooling decreases, unnecessary reheating of make-up air supply is reduced.

8.3.2. Heating and Cooling Coils

Heating coils are supplied by hot water from high efficiency hot water boilers and a heat pump.

Pre-heat/re-heat coils, batteries and room radiators are also supplied with hot water. Steam or electricity are not normally be used. A conscious design change to use low temperature/hot water heating will facilitate the use of combined heat and power [20] or renewable energy sources in the future.

Cooling coils are supplied by chilled water.

Variable refrigerant volume systems are always evaluated for buildings with simultaneous heating and cooling loads [21].

Coils are designed to minimize air flow pressure drop. Coil tube velocities are limited to improve holding time and increase heat transfer.

Hot water and chilled water coils are modulated by two port valves fed by variable flow constant pressure circulation systems to minimize pumping loads.

Floating temperature control of central Air Handling Unit heating/cooling plant is link to control of terminal plant to minimize heat/cool conflict.

Cooling to dew point only takes place at times when dehumidification is necessary.

Temperature probes are installed, and the building monitoring system is designed to detect failed control valves on heating and cooling coils (a frequent cause of significant wastage of energy).

8.3.3. Heating and Cooling Ductwork

High standards of ductwork insulation are applied.

8.3.4. Decentralized Heating Systems

Decentralized space heating systems provide an energy efficient solution where demand is intermittent, or service distribution runs are long. This could include localized gas fired air heaters or Low Temperature Hot Water (LTHW) radiators fed from high efficiency gas or oil-fired boilers [22].

8.4. Dehumidification

The most energy efficient method of dehumidification is evaluated for each application:

- Dew point refrigeration
- Solid desiccant
- Liquid desiccant

The evaluation takes account of humidity and temperature set-point and dead-band requirements against local climatic conditions.

For desiccant systems precooling is considered. Regeneration heat is from the most energy source (hot water in this case study).

Where hydroscopic products are exposed, low relative humidity air is required. Therefore, we try as much as possible to minimize the room volumes.

We also segregate areas to avoid feeding low relative humidity into entire manufacturing spaces.

We ensure dehumidification units are used with energy minimization features (i.e., regeneration air to air and heat recovery).

Desiccant dehumidifiers are more economical than refrigeration-based dehumidifiers below 45% RH.

Liquid desiccant dehumidifier [23]:

As seen in Figure 13, a liquid desiccant comprises one absorber mechanism with strong liquid desiccant and one regeneration mechanism with dilute liquid desiccant.

Dry desiccant dehumidifier (with heat recovery):

All dehumidifiers of this case study are dry desiccant dehumidifier. They are all fitted with a technology named PowerPurge™ and developed by the company Munters (dehumidifiers manufacturer). The principle of this equipment is described in figure 14.

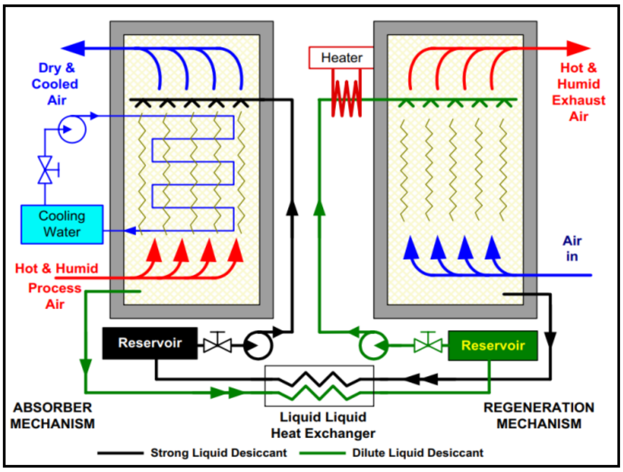

Figure 13. Liquid desiccant functioning principle [24]

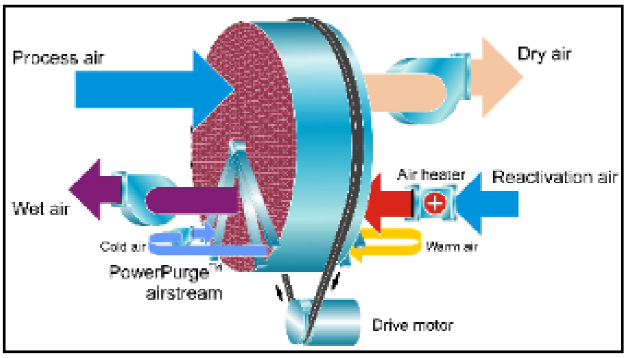

Figure 14. Munsters rotor principle with PowerPurge™ [25]

We ensure dehumidification units are used with energy minimization features (i.e., regeneration air to air heat recovery). A desiccant dehumidifier has a desiccant wheel that rotates slowly between two primary airstreams, process, and reactivation. In the process airstream water vapor is removed as it passes through the desiccant wheel. This dehumidified air is then delivered to a manufacturing process or space. The wheel then rotates into the reactivation sector where a heated airstream is passed through the wheel. The desiccant wheel releases the water vapor to this airstream. Most of the energy required for the desiccant process is used in heating the reactivation airstream. PowerPurge™ saves energy in two ways. The unique patented PowerPurge™ acts as an energy recovery system, collecting waste heat off from the hottest section of the desiccant wheel and using it to help with reactivation. This reduces the energy required for reactivation while also reducing the discharge temperature of the process air, resulting in lower energy costs for post cooling.

PowerPurge™ can also save on first cost. Equipping a desiccant system with PowerPurge™ can reduce the size of the desiccant rotor without diminishing the dehumidification capacity, while still seeing a savings in energy costs.

All dehumidifiers on site are dry desiccant dehumidifier. HVAC 6 dry desiccant dehumidifier have been changed by two with heat recovery.

8.5. Ductwork

Ductworks and fittings are designed and sized for low air velocity (e.g., 10% oversized will deliver 20% less fan pressure for the life of the system). Ductwork and fittings are also designed and installed to provide lowest practicable frictional resistance/losses, with minimum balancing requirements [26].

High efficiency diffusers are used to minimize pressure drop. Ductworks are also designed, installed, and tested to minimize leakage.

Supply air and extract fans ductworks are located close together to facilitate heat recovery.

8.6. Installation & Commissioning

One of the most common issues of high energy use in HVAC is caused by poor or nonexistent commissioning [27]. Fans, filters, ductworks, and fittings including bends, louvers etc. are installed with care to minimize frictional losses and pressure drops. Care is taken during commissioning to ensure that air flows, pressure drops, and fan power is minimized in accordance with the scheme design. A careful and thorough commissioning is done for each HVAC (e.g., commissioning checklist and validation documentation are carefully prepared).

9. Fourth Step: Efficient Air Treatment by Management

Systems will over time drift from operation set points. A continuous maintenance regime is very important to sustain energy efficiency [28,29]. Consequently, a program of system survey review, maintenance and recommissioning is established for all HVAC.

9.1. Filtration

Filter pressure drop is monitored by electronic pressure differential indicators. Filters are replaced (with high efficiency filters) regularly to minimize pressure drop.

9.2. System Balancing

Air flows and pressure drops are measured at appropriate intervals to ensure compliance with the detailed specification (and good manufacturing practices requirements where appropriate).

9.3. Coil Cleaning

The air side of coils are regularly deeply cleaned and protected using specialist treatment such as Coil-Flo™. This operation permits to reduce air side pressure drop increasing fan loads, and to promote more efficient heat transfer [30]. In HVAC with high fresh air rate, the cleaning frequency is higher.

9.4. Fans

Allowances are made in the design to ensure eroded/fouled fan blades can be readily removed, obstructions to air intakes cleared and dampers freed etc. during maintenance. Thanks to EC.

9.5. Duct Leakage and Repair

Supply and extract duct leakage are all identified. Routine inspections are in place and repairs are done as soon as possible. Duct insulations are also repaired as soon as possible.

9.6. Thermal Image

Thermal Image camera survey of AHU's, ducts, cold/hot water pipes and fabric is done regularly. All poor or no insulation and all leaking (valves etc.) are fixed quickly.

9.7. Building Management System

"Building Management System (BMS) is a high-technology system installed in buildings that controls and monitors the building's mechanical and electrical equipment such as air handling, fan-coil unit, cooling plant systems, lighting, power systems, fire systems, and security systems". "The objective of a BMS is to achieve more efficient building operation at reduced labor and energy costs and to provide a safer and more comfortable working environment for building occupants" [31].

The BMS used in this case study control and monitor: Central HVAC units; Packaged plant; Terminal unit (Variable air volume and fan coil units); Central and dispersed boiler plant; Chillers; Unitary air conditioning systems (roof top units).

Regular diagnostics and optimization of the control strategies are in place.

The diagnostics will identify energy savings improvements related to:

- Set time schedules for occupancy
- Room conditions (temperature/relative humidity) at lower end of allowable range
- Non-production hours set back overlapping of heating and cooling stages (i.e., eliminate heating/cooling systems "fighting")
- Heating/cooling valves bypassed (in manual)
- Heating/cooling control valves at 100%
- Set point control tolerances; dead bands; Control is set to manual; Set point is not being achieved
- Pressure regimes and filtration pressure drops
- Heating and cooling control valve actuators are checked to ensure seats are not passing
- Fan speed is set to 100% (not dynamically controlled)

9.8. Proportional, Integral & Derivative Control Loops

A poor control loops will increase energy consumption.

The goal of tuning a PID loop is to make the control stable, responsive and to minimize overshooting [32,33]. These goals, especially the last two, conflict with each other. It is necessary to find a compromise between responsiveness and minimal overshoot as shown in figure 15.

It is also a key element for reducing wear on valves/actuators/dampers etc.

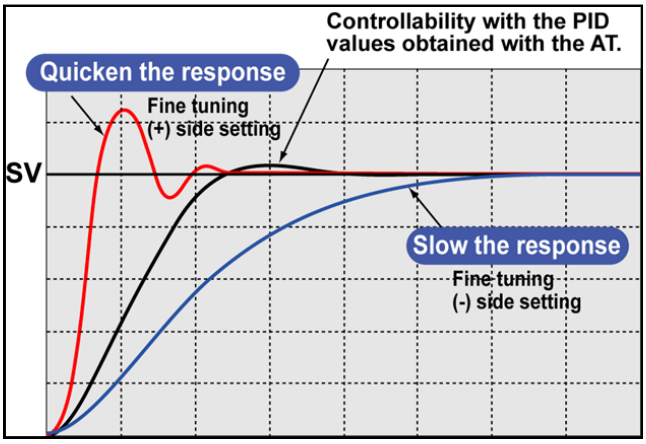

Figure 15. PID controls Loop

As a rule of thumb, actions are taken if any controlled device is cycling as in figure 16 with an amplitude greater than 20% of its full range or is changing position by more than 20% in a period of 10 minutes.

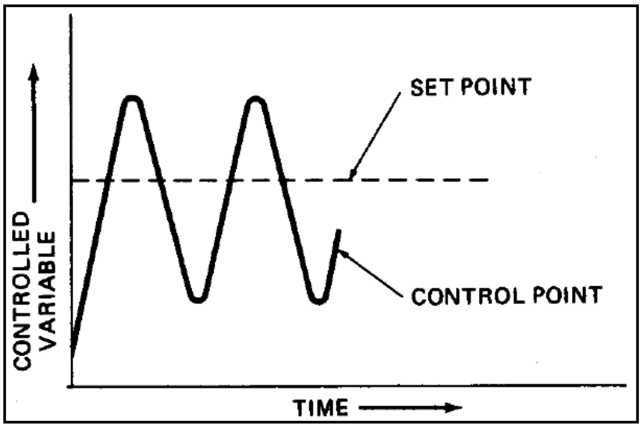

Figure 16. Poor variable control

9.9. Verify Performance is Maintained

System performance will degrade over time and therefore energy consumption will increase as represented in figure 17:

- If no monitoring/intervention is made, then most improvements will be undone within 12-24 months.
- People love to fiddle with controls – often get over a temporary problem, but then forget to fix the root cause. e.g., put control in manual.

A disciplined approach has been introduced to track changes:

- Energy impact analysis for all changes by site energy expert.
- Routine monitoring (part of routine maintenance practice and metering is a helping).

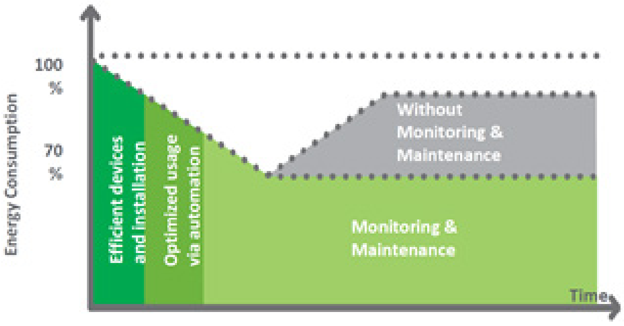

Figure 17. Energy management impact on consumption over time

10. Results

HVAC 4 is one of the major HVAC and it covers the warehouse in manufacturing area. Table 4 contains the different actions done in 2019 (quarter 4) for reducing its carbon emissions.

As seen in table 5, total electrical consumption of HVAC 4 has been reduced by 68 231 kWh (-57%) in 2020 (vs 2019). It represents 4, 7 CO2 tons reduction and this result has been obtained with nearly the same volume of production.

HVAC 8 is also one of the major HVAC and it covers the secondary packaging area. Table 6 includes the different actions done in 2019 (quarter 4) for reducing its carbon emissions.

As shown in table 7, total electrical consumption of HVAC 8 has been reduced by 78 247 kWh (-43%) in 2020 (vs 2019). It represents 5,4 CO2 tons reduction and this result has been obtained with nearly the same volume of production.

Table 4. Modifications on HVAC 4 in Q4 2019

HVAC 4	**Air change rate (volume/hour)**	**Dead-band (occupied mode)**	**Motors & Fans**
Before	12	No dead-band: setpoint 20°C	- Supply return air fan: 1 motor; 36 kW; Direct transmission - Return air fan: 1 motor; 15,5 kW; Direct transmission - Air fresh unit: 1 motor; 3 kW; Direct transmission
After	8	20°C to 21°C	- Supply return air fan: 10 motors; 3,9 kW; EC Motors - Return air fan: 3 motors; 6 kW; EC Motors - Air fresh unit: 1 motor; 1,9 kW; EC Motors

Table 5. Electrical Consumptions of HVAC 4 in 2019 and 2020

HVAC 4 consumptions kWh	**2019**	**2020**
January	5284	3402
February	5202	4488
March	5391	3342
April	11218	3762
May	29850	4643
June	23402	4452
July	9496	4498
August	9835	4935
September	5879	4649
October	5624	3547
November	4910	3831
December	2787	5098
TOTAL	**118878**	**50647**

Table 6. Modifications on HVAC 8 in Q4 2019

HVAC 8	**Air change rate (volume/hour)**	**Dead-band (occupied mode)**	**Motors & Fans**
Before	7	No dead-band: setpoint 20°C	- Supply return air fan: 1 motor; 18,5 kW; Direct transmission - Return air fan: 1 motor; 11 kW; Direct transmission - Air fresh unit: 1 motor; 3 kW; Direct transmission
After	5	18°C to 20°C	- Supply return air fan: 4 motors; 6 kW; EC Motors - Return air fan: 3 motors; 6 kW; EC Motors - Air fresh unit: 1 motor; 3,9 kW; EC Motors

Table 7. Electrical Consumptions of HVAC 8 in 2019 and 2020

HVAC 8 consumptions kWh	2019	2020
January	11582	10486
February	13307	8854
March	15382	9744
April	13009	8714
May	15648	7681
June	17512	9342
July	21816	8188
August	11760	8136
September	17139	10150
October	20063	7973
November	15451	6768
December	9786	8172
TOTAL	**182455**	**104208**

Table 8. First Actions of HVAC 6 Replacement by HVAC 33 and 34 in 2020

HVAC 6 to HVAC 33 & 34	Air change rate (volume/hour)	Air fresh reduction	Segregation
Before	15	10%	One HVAC
After	12	5%	Two HVAC

Table 9. Other Actions of HVAC 6 Replacement by HVAC 33 and 34 in 2020

HVAC 6 to HVAC 33 & 34	Dead-band (occupied mode)	Motors & Fans	Filters energy efficiency
Before	No dead-band: setpoint 20°C	- Supply return air fan: 1 motor; 26 kW; Direct transmission - Return air fan: 1 motor; 26 kW; Direct transmission - Air fresh unit: 1 motor; 2,3 kW; Direct transmission	D
After	18°C to 20°C	**HVAC 33** - Supply return air fan: 4 motors; 5 kW; EC Motors - Return air fan: 4 motors; 4 kW; EC Motors - Air fresh unit: 2 motors; 2,4 kW; EC Motors **HVAC 34** - Supply return air fan: 4 motors; 5,2 kW; EC Motors - Return air fan: 4 motors; 5,2 kW; EC Motors - Air fresh unit: 2 motors; 2,4 kW; EC Motors	A

HVAC 6 has been replaced by 2 new HVAC: HVAC 33 and HVAC 34. A set of actions have been done to minimize energy consumption and therefore carbon emissions. Table 8 summarizes those actions:

Table 9 above comprises details of the second set of actions done for HVAC 6/HVAC 33 & 34.

Thanks to those main actions energy consumption of HVAC 6 has been reduced by 1/3 (from 260 667 kWh to 173 778 kWh). It represents 6 tons of CO2.

Several other actions have been done on others HVAC in those last three years and on chilled water production: insulation improvement, regulation optimization (example: regulation based on rooms humidity and not fixed setpoint), heat recovery on dehumidifier, ductwork revamping, heat pump on chiller water installation etc.

As shown in table 10, HVACs carbon emissions have been reduced by 24% in 3 years with nearly the same volume of production (85 CO2 tons).

Table 10. HVAC Electrical Consumption Evolution from 2018 to 2021

Electrical consumptions (kWh)	2018	2021
HVAC Dehumidification	991 858	726 175
HVAC Motors	2 494 617	1 914 121
Chilled water production	1 608 581	1 224 793
Total	**5 095 056**	**3 865 089**

11. Conclusions

In industrial environment, HVACs are generally among the high consuming equipment. Without a proper strategy their consumptions can continuously increase and therefore their carbon emissions.

The methodology defined and deployed in this case study is a tiered methodology starting by the design and ending by the management. The methodology can be applied to similar industrial sites and even to administrative or commercial buildings fitted with air treatments systems.

The application of this methodology has permitted to reduce HVACs carbon emissions by 24% in 3 years while HVAC represents more than 55% of site's carbon emissions.

Abbreviations

AC = Alternative Current
AFU = Air Fresh Unit
AHU = Air Handling Unit
BMS = Building Management System
CO2 = Carbon dioxide
CHP = Combined Heat and Power
DC = Direct Current
DSH = Dehumidifier
EC = Electronically Commutated
HVAC = Heating, Ventilation and Air Conditioning
LTHW = Low Temperature Hot Water
PID = Proportional, Integral & Derivative
RH = Relative Humidity

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