TOWARDS ZERO ENERGY HOSPITAL BUILDINGS – ENERGY SAVING OPPORTUNITIES IN STEAM AND HUMIDIFICATION INSTALLATIONS

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Abstract. The healthcare sector is highly energy intensive with circa 6% of the total global energy consumption. For this reason, hospitals strive to reduce their energy usage, especially of the most energy intensive systems like steam and humidification installations. Centralized steam plants are widely used by hospital complexes since many hospital functions rely on steam to properly fulfil its purpose (e.g. air humidification, sterilization, space and water heating, kitchen boilers). Central steam plants are not the most energy-efficient method to supply the consumers' demand due to the high energy and fossil fuel consumption for steam production and the consequent losses inherent to the extensive distribution installations. In general steam losses in steam system can represent over 30%. Total CO2 emissions for steam production can be over 20% of which humidification can represent over 50%. Therefore reducing the steam demand for humidification and implementing decentralized systems is of great importance for Hospital Buildings to fulfil for new buildings the nZEB requirements. In this paper the results of a literature study are presented and a method based on the so-called 5-step method [1] and the Kesselring method is used to select different systems based on their performances on different aspects. Solutions are presented that can save more than 50% of energy use and CO2 emissions used for the steam production.

Keywords. CO_2 emission reduction, Energy Savings, Hospitals, nZEB, Steam, Humidification, Sustainable Healthcare, Users Comfort, Infection Prevention.
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1. Introduction

The need for (net) Zero Energy Buildings (nZEBs) is of increasing relevance due to climate change, rising energy prices and scarcity of fossil fuels. The built environment in the Netherlands is a great contributor to the overall energy consumption; according to IEA statistics, the sector has 46% of the total energy consumption share in 2016 [2]. The measures of the National Climate Agreement in the building sector aim to enhance energy efficiency by no longer enabling new buildings to be heated with natural gas and improving the existing building to fossil-free heating production.

The healthcare sector is highly energy intensive with circa 6% of the total global energy consumption. For this reason, hospitals strive to reduce their energy usage, especially of the most energy intensive systems like steam and humidification installations. In this context, the Dutch University Medical Centers (UMCs) consume approximately 64% of the healthcare demand [3].

The UMCs have a growing concern to fulfill the nZEBs requirements due to legislation. One of the many possibilities to decrease the energy consumption of hospitals is to re-evaluate the role steam plays in this environment. Steam use is a widespread method through many healthcare facilities. Since steam is considered a sterile medium, it can be used in hospitals for many different purposes, such as air moisturization, autoclaves, space and water heating, kitchen boilers and laundry. In hospitals, air humidification by steam has traditionally been used as part of the air treatment installation. The main arguments for this are the prevention of nosocomial infections, patient and staff comfort, safety (electrostatic discharges) and maintaining equipment good functioning. Such a form of air humidification, however, is associated with high energy consumption. According to the TNO report [4], approximately 20-60% is used for air humidification. Moreover, thermal energy losses happen in flow distributing pipes where up to 30% of the total gas consumption of the steam boilers are lost.

The current study evaluates from a sustainability perspective, how to decrease energy consumption associated with steam in a building complex by using one of the Dutch UMC's as case study: The Utrecht Academic Medical Centre with ca. 400,000 m^2 buildings.

2. Methodology

The main objective of the research was to understand which are the main steam consumers of a hospital environment and, identify and recommend through functional analysis energy-efficient alternatives for the most significant consumer. Next a strategy was developed that can be applied in different hospital cases to identify energy reduction opportunities and measures that accelerate the path to nZEB hospital buildings and answer the main research question: Which measures can hospitals take for making the transition from centralized steam humidification to a more sustainable solution with less CO_2 emissions?

The literature research conducted for this study investigated the need for humidification and the ongoing debate that surrounds this topic. The research focuses on the influence of low relative humidity (RH) on health problems [5][1] and users' comfort. Furthermore, it provides an overview of all the other steam consumers within a hospital environment. Also, research was performed to give an overview of the possible alternatives for steam replacement in certain processes that could lead to energy reduction. In order to validate and assess the possible CO_2 emission reductions , data was gathered from the Utrecht Academic Medical Centre with actual measurements of steam used by each consumer and its energy consumption. A Pareto [6] energy analysis is applied to identify in the case study the main steam consumers and their overall energy share. The major energy consumers are identified on the campus level. In the development of the scenarios, the Pareto analysis is applied to the determined major consumer that can be improved and result in most energy reduction in comparison with the current situation (base case scenario).

The reduction of the energy demand is investigated through the evaluation and decision making supported by the Kesselring method [7]. This method consists of placing the possibilities in a morphological overview to generate different scenarios for energy consumption reduction. This morphological overview is used as a tool to structure the development process. The current scenario of the steam users is placed alongside the available alternatives for each function and humidification production method. This forms a matrix of possible solution combination scenarios. Scores are defined to rate the scenarios on multiple aspects, which are the criteria on which the possibilities should be evaluated.

The determined values are aggregated into a score for the overall rating of each alternative scenario and compared with the current base case scenario. The visualization technique, developed by Kesselring, allows different variants to be compared with each other. Within this method, the criteria for the requirements are separated into the categories for functionality and realization. The results of such evaluation can be seen in the so-called S-(Stärke) diagram [7]. Among the possible scenarios, the most viable options lie near the diagonal and have higher scores.

3. Case Study

As previously explained, the steam production is supplied to different functions. Each of these functions has different steam/energy demands. In order to statistically determine which of these different functions cause the most significant effect on energy demand, the Pareto Analysis technique is performed.

The Pareto Principle, explains that a small number of causes can be responsible for a large percentage of effects. This technique is particularly used to improve the decision-making process and efficiency.

The first step to applying such a technique is to identify and list all the causes (e.g. steam consumers) that may be leading to an issue (e.g. high energy consumption). Once all factors are known it was possible to identify the main contributors to the problem that needs to be solved.

There were no measuring sensors for quantifying the steam input for the air humidification of each separate building of the complex. This made the process of identifying inefficiencies and possible strategies more difficult. Therefore the assessment was based on the specifications of steam-equipment and its usage, feedwater metering and water-mass balance calculations (based on feedwater and condensate return metering). This resulted in the steam consumption share per steam consumer presented in Figure 1.

[1] The conclusions presented on this reference is that RH has little or no effect on reduction of infection risk, although the effect of RH on the susceptibility of the SARS-CoV-2 virus was not considered and will be further investigated.

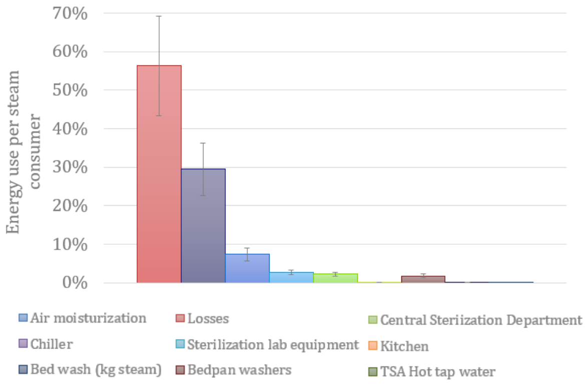

Fig. 1 - Steam consumption share per steam consumer

The steam energy consumption can then be divided into three main streams: air humidification, distribution losses, and other steam consumers. Data retrieved reinforces the information obtained on literature that steam losses represent a great disadvantage on buildings systems and that air moisturization is the largest consumer of steam in hospital applications. In the case study, the losses represent 29% (with ±23% of inaccuracy on the calculations, given the lack of precision of measuring sensors).

There is no sub-metering for the air humidification in each of the UMC buildings, however by making use of the typical functions area and their percentual area in each of the buildings it is possible to make an estimation of the energy consumption used for the humidification of each building and function. Figure 2 shows the functions that consume more energy on the UMC per net internal area (NIA). It reinforces the assumption that operation theatres/rooms (ORs) are the most energy demanding per m² in regard to their humidification systems.

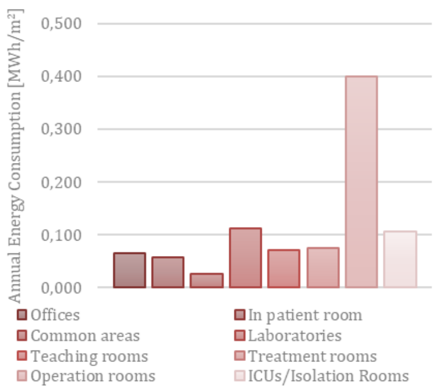

Fig. 2 - Annual energy consumption per NIA

Nevertheless, a Pareto analysis can also be used to determine which of the room functions are the major contributors in the overall UMC air humidification consumption. Figure 3 shows that despite the ORs requiring more energy for air humidification per area, offices and the common area are the major contributors to the overall consumption.

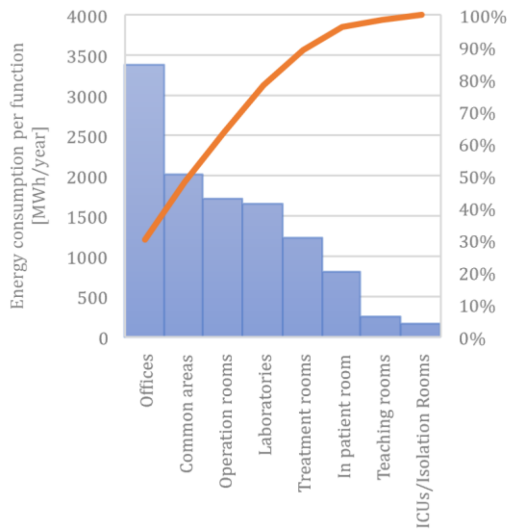

Fig. 3 - Pareto analysis of the room functions as contributors to the air humidification energy consumption

The analysed UMC has around 132,000 m² of offices and common areas that are daily humidified and herewith contributing 30% and 18%, respectively, the humidification energy consumption at this complex.

The results show which specific hospital functions are consuming large amounts of energy for their air humidification. It is necessary to discuss whether air humidification is really necessary and considerably contributing to the healing process to function properly and/or to significantly increase their building users' health and comfort.

4. Scenarios Evaluation

4.1 Kesselring Method

The functional aspects of air moisturization are very subjective and controversial. No exact values of each system's influence on users' health, comfort and ESD are given in the literature. Thus, this evaluation is only an estimation of the relation between these aspects, based on the opinion that was acquired by performing the literature study. The scores are given based mostly on the literature study. On the other hand, the realization aspects are measurable; thus, they represent the most significant difference in the comparison between the scenarios.

The functional criteria are based on:

• Health concerns: the highest score refers to the low impact on nosocomial infection threats, fungi growth and allergy symptoms, according to literature, assuming the implementation of the scenario.

• Electrostatic discharge prevention: scores high when the ESD possibility is the lowest when compared to other options.

• Users Comfort: scores high when the patients or staff comfort is believed to be improved, with the implementation of the scenario, according to the literature study.

The realization aspects are:

• Energy efficiency: the highest score refers to the highest energy saving potential of the scenario (≥75% than the baseline scenario).

• Carbon Emissions: scores high when the carbon emissions reduction potential of the scenario is very significant when compared with the baseline (≥75%).

• Operational costs: a high score means the scenario has low annual operation (energy + water treatment) costs when compared to the other scenarios.

• Investment costs: scores high when the estimated investment costs of the scenario are relatively low when balanced with its returns.

• Realization time: the highest scores are given when the scenario can be implemented in a short time span.

• Controllability: scores high when the scenario counts with a good RH-range control

4.1 Baseline scenario

In order to make a viable energy reduction comparison, a reference profile is needed. The energy consumption for air humidification in the whole campus for the year 2018 (≈12,945MWh) needs to be validated through calculations of a baseline scenario. Using calculation and formulas based on the Mollier diagram and internal setup points for the air treatment of the case study UMC, a baseline scenario matching the energy consumption data of 2018 was simulated. The resulting annual consumption for air humidification of the baseline is 12,274MWh, which represents 95% accuracy when compared to the gathered data.

The scenarios' energy calculations were based on the requirements for each typical hospital function (e.g. patient's rooms, operating rooms, offices, etc). The indoor temperature, RH levels range and air changes per hour (ACH) data were based on the UMC current or future requirements listed on its 2018 Masterplan. When the value in the masterplan is neither mentioned or required, recommended values from ASHRAE [8, 9, 10] or CBZ [11] are used.

The functions considered in the calculations represent the most important functions in a university hospital building and have relatively different air treatment requirements: offices, in patient, common areas, laboratories, teaching rooms, diagnostic and treatment, operating rooms and isolation room/ ICU.

1.1 Alternative scenarios

One of the goals of UMC's is to reduce the use of fossil fuels (e.g. natural gas) as its primary energy source. Thus, for the simulated scenarios, local electrical humidifier (isothermal) option to produce steam, adiabatic humidification process and use of energy wheel options are introduced.

Seven scenarios are analysed. These were created by combining alternatives from a Morphological Overview. The combinations are based upon different air humidification and energy efficiency concepts. Not every possible combination of the presented solutions, even with focus only on the air moisturization, is possible, since having different air treatment systems can lead to logistical problems in the hospital.

Scenario 1 – Reduced RH ranges

Scenario 1 is simulated considering the minimum RH levels for all rooms as recommended by ASHRAE [8, 9, 10]or the CBZ [11]. The humidification is maintained as isothermal, with the same steam production method, to be able to compare the benefits this scenario can bring when compared with the baseline. The total area to be humidified in this scenario is the same as the baseline scenario, 195,000m^2.

Scenario 2 – Reduced functions with air humidification

Scenario 2 is calculated according to the assumptions that not all rooms are supplied with moisturized air. Considering that air humidification is not a priority in all building's rooms, but only in the rooms that have stricter RH requirements, scenario 2 is simulated considering only the most crucial rooms for the patients' health: ORs and ICUs/isolation rooms. With the purpose of comparison with the baseline, the only change is on the building's functions, which are reduced; all the other parameters (e.g. RH levels, steam production method) are the same as the baseline.

The total area to be humidified is reduced to approximately 5,890 m^2, to be supplied with steam by the central energy plant.

Scenario 3 – ORs and ICU with electric humidification

This scenario is simulated as scenario 2; however, the difference is that this one assumes the local use of resistive humidifiers, instead of natural gas as a source for the steam production. The choice for this type of electrical humidifier was determined due to its advantages found during the literature study.

The total area to be humidified is reduced to approximately 5,890 m^2. The electrical humidifiers should be placed at a local level (in-duct).

Scenario 4 – Adiabatic in most building's functions

An alternative for steam in air humidification is the use of atomizing humidifiers, also known as adiabatic humidifiers. On this system, the water is vaporized in micron size droplets directly into the air. In the Netherlands, a report from TNO [12] describes the proper water treatment for being used in this type of system and states that adiabatic humidifiers types - without recirculation - are suitable to be used in healthcare facilities. Nevertheless, the report [12] recommends ORs and ICUs remaining with humidification being provided by steam.

Adiabatic humidification is the most likely future for humidification in large buildings since it is more energy-efficient than the isothermal type. In order to verify the energy efficiency of the proposed system, this scenario evaluates what would be the benefits of applying low-pressure adiabatic humidification to all rooms, except ORs and isolation rooms/ICUs, with the same RH levels as the baseline.

Moreover, scenario 4 considers that ORs and isolation rooms/ICUs have their humidification provided by locally produced steam electrical humidifiers. Thus, 188,800 m^2 are humidified by adiabatic technology; the adiabatic humidifiers should be placed at a central level (in approximately 100 AHUs). The remaining 5,890 m^2, or 226 rooms, are considered to be locally humidified by electrical (resistive) humidifiers.

Scenario 5 – Adiabatic for all rooms

A relatively new technology that has been applied in a few Dutch hospitals[2] is the hybrid adiabatic humidifier. This adiabatic humidifier hygiene has been tested, proven and confirmed by the award of the SGS-Fresenius Hygiene Certificate. Given the fact that this technology is already in use in the Netherlands and it has received a well-known hygiene certificate, its energy consumption and benefits to the case study are considered in this scenario. This technology has already been applied in one Dutch hospital with this type of humidifier applied to its ORs; therefore, this scenario takes this application into consideration for all building functions.

Scenario 6 – No humidification for most rooms + adiabatic

According to the research, humidification does not play a big role in many building areas. As previously stated, assuming a scenario wherein the Dutch hospitals do not use air moisturization in the majority of its buildings functions, is, therefore, a reasonable option.

However, for the middle-term, it is safer to consider that a few rooms will still need air humidification. In this scenario, humidification is considered in rooms that are focused on the most crucial patient treatment. This scenario assumes that only the AHUs which supply air to operating and isolation/ICU rooms of UMC to be equipped with the same adiabatic humidifier type of the previous scenario.

Scenario 7 – Energy recovery wheel

Heat and moisture recovery from mechanical ventilation air with energy wheels can be used if it is prevented that the possible suctioned contaminants are not returned to the supply channel. In regard to hospital environments, it is necessary to ensure there is no cross-contamination in specific treatment areas, such as intensive care and operation rooms. Therefore, this scenario considers the implementation of energy wheels for all the departments, except for the intensive care/isolation rooms and operating department. These are assumed to receive air moisturization via local use of resistive humidifiers (same as Scenario 3).

5. Results

5.1 Baseline

The baseline scenario considers that the air moisturization consumes 12,274 MWh/year, based on calculations regarding the isothermal air humidification process. The energy costs of the steam production for the baseline scenario consist of the costs for natural gas for steam production and the costs for the feedwater. The annual humidification load requires approximately 30,000m^3 of water per year.

Calculations are made for this per kWh and m^3 of input, considering:

• Natural gas rate ≈ € 0,0384/ kWh [13]

• Feedwater rate ≈ € 0,7211 / m^3

• Softened water treatment ≈ € 1,1012 / m^3

The annual energy costs and consequently CO_2 emissions for the total steam production of the baseline scenario can be seeing on Table 1.

5.1 Alternative scenarios

The results for the realization aspects to be evaluated are presented on Table 1.

[2] Examples are: Deventer ziekenhuis (in its operating rooms); Antonius ziekenhuis; Radboud UMC; ZGT ziekenhuisgroep Twente; VUMC

Tab. 1 - Summary of the Scenarios

Scenario	Energy Consumption [MWh/year]	Carbon Emissions [ton CO_2/year]	Energy Costs [€/year]
Baseline	12,274	2,250	525,300
1	4,200	770	167,300
2	3,000	350	130,100
3	3,000	1,040	273,900
4	11,780	3,730	1,264,100
5	9,650	3,280	1,106,800
6	300	100	99,300
7	2,200	750	205,000

Scenario	Operational Costs [€/year]	Investment Costs [€]
Baseline	2,626,500	-
1	836,500	-
2	650,500	-
3	1,369,500	>4,000,000
4	2,275,380	>7,000,000
5	1,992,240	>3,000,000
6	496,500	>1,040,000
7	1,025,000	>8,200,000

The scoring for functional and realization aspects was performed by assembling the aspects on matrixes of comparison (which aspect should carry a higher weighing factor) and evaluated on a grading system between 1 to 4 (e.g. 1 = scenario choice is the least recommended choice; 2 = scenario has some positive influence, however it is not very significant to the overall context; 3= scenario has a positive influence in large part of the case study; 4= is the most recommended choice). Each of the involved parties on this research has given their own score based upon knowledge acquired by literature study, professional experience and results from the calculations made for the realization aspects.

Figure 4 presents the summary of the scenarios' score for each of these aspects. The graphical result of the scoring is shown on the Kesselring diagram in Figure 5.

Air Moisturization								
	Max	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**
Function								
Health concerns	24	12	12	12	18	21	15	18
Eletrostatic discharge prevention	8	3	3	3	6	6	5	6
Users Comfort	8	3	3	4	7	7	4	6
Total	40	18	18	19	31	34	24	30
Percentage of whole	**100%**	**45%**	**45%**	**48%**	**78%**	**85%**	**60%**	**75%**
Realization								
Energy efficiency	24	15	21	21	6	9	24	21
Carbon Emissions	24	12	21	15	3	3	24	12
Operational costs	16	6	14	10	2	4	16	10
Investment costs	16	16	16	6	4	6	12	4
Realization time	8	8	8	5	2	3	5	2
Controllability	8	2	3	6	6	7	5	5
Total	96	59	83	63	23	32	86	54
Percentage of whole	**100%**	**61%**	**86%**	**66%**	**24%**	**32%**	**90%**	**56%**

Fig. 4 – Summary final scoring of scenarios

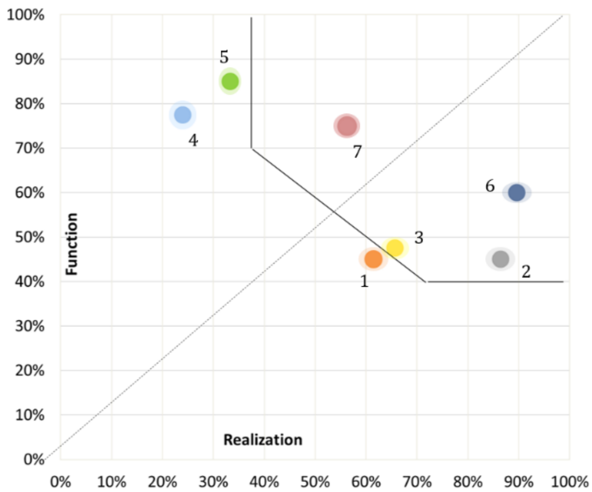

Fig. 5 - Kesselring Diagram final scoring of scenarios

As short-term solutions, maintaining steam as the humidification method, scenario 1 and scenario 2 represent energy consumption improvements. By decreasing the RH levels to the minimum recommended by ASHRAE (scenario 1) or reducing hospital areas that are humidified to only the ones that have more strict requirements regarding the RH levels (scenario 2), both are solutions that can be applied in a short time span with no investment costs. These are the solutions with the lowest financial costs since in the UMC case study there is already a power plant to supply the steam demand. However, both assume that the production of steam would still be made with natural gas, which is not the most sustainable solution, considering the long-term goal of reducing fossil fuel use. Additionally, even with the reduced demand of these scenarios, the steam losses are still implied in the overall system energy consumption.

Scenario 3 considers the same parameters as scenario 2; however, scenario 3 requires investment costs for the application of electrical humidifiers, whereas the latter does not require any initial investments. The electricity costs also make this an unattractive choice. Nonetheless, advantages of this system are not using natural gas as a primary energy source; also, once the main steam consumer has its demand locally supplied, the system losses are reduced as the centralized plant would no longer be required.

Scenario 4 and 5 scored the highest in the function aspects had poor scores on realization aspects. It can be assumed that it has received high scores in functional aspects because both scenarios consider humidified air being provided to all hospital areas, eliminating any health, electrostatic and discomfort risks for all users. Nonetheless, the implementation of adiabatic installations for all buildings would imply high investment costs, long realization time; moreover, the electricity consumption and carbon emissions would be higher than the current scenario, which can be assumed to be the reasons for the poor scores on realization aspects. For improving these scenarios scores in the realization aspects, the functions which are supplied with air humidification via adiabatic systems should be reduced, in order to reduce the investments and operational costs.

Scenarios 2, 3 and 6, that only consider a few hospital areas to be humidified, are the most promising ones, as the investment costs can be compensated in a few years, maintaining the areas which have more strict requirements humidified and having low energy consumption.

Scenario 6 is the most energy-efficient case in which only two types of hospital functions are considered and supplied with a highly efficient humidification system. Nonetheless, the investment costs are still very high and time for realization can be rather long.

Scenario 7 is the most beneficial for all hospital zones: with the energy wheels implementation in all building parts, humidity levels could be kept within the comfortable range, which could improve the perceived indoor air quality. Moreover, the functions with stricter requirements are considered to be supplied with steam via electrical local humidifier, to ensure no health risk to the patients. However, the investment costs and the realization time are very high in this scenario.

It can be assumed that a combination of alternatives, that would result in RH levels within the comfortable range for all hospital areas, would be the most optimal solution, such as scenario 7. With the use of energy recovery wheels in large part of the hospital, there would be no need of humidification being supplied via isothermal or adiabatic systems; this solution has a great reduction of costs and energy consumption when compared to the other scenarios; additionally, scenario 7 assumes the supply of air humidification via a sterile medium (steam) in the most strict areas of the hospital, thus guaranteeing a high score in all functionality aspects. However, this scenario could be improved if adiabatic systems were assumed instead of electric humidifiers: the electricity costs would be fewer and the overall energy efficiency would be improved.

The obtained values are an estimation of the energy, CO_2 emissions and costs savings of what the scenarios could represent if applied to the case study under these assumptions. There are many other variables which were not taken into account as the study case is a complex of several buildings each one with different characteristics and occupation profiles.

Investments' costs for the adiabatic and energy wheel systems are difficult to determine since adjustments are needed in the air handling units and ducts, particularly in the humidification sections. The existing steam system does not require any investment.

The complex heating and cooling demands would be affected by alternative systems choice. However, they are outside of the scope of this research. Their assessment would require extensive research focused on these systems alone. The focus is the air humidification, the recommended levels of air RH and possible alternatives for the steam demand. Research has shown that there are feasible paths to significantly reduce energy consumption in this system.

6. Conclusions

The main conclusion of this study and case evaluation is that hospitals have massive energy and CO_2 emission reduction possibilities by humidifying when necessary, or significantly beneficial, and applying alternatives for centralized steam plants.

The main starting point is the fact that many large hospitals have their own central plant to produce and distribute steam to its many consumers. This system, however, results in large amounts of CO_2 emissions and energy losses. In this study a strategy is developed that hospitals can apply to assess and evaluate alternative solutions for humidification and the central steam plant.

As an initial step of the aforementioned strategy an assessment of the hospital areas where humidification is not essential should be conducted, humidification demand reduced and investing on localized air humidification in crucial areas of the hospital. From a long-term perspective, investment on the adaptation of the whole hospitals' systems is required.

To ensure comfort in the majority of buildings' functions, energy-efficient energy wheels are the most optimal choice. The areas which may still need air humidification to be supplied by other means could have local systems, either electrical steam humidifiers or adiabatic. By transitioning from centralized steam plants to localized solutions, the Dutch hospitals could guarantee energy savings, CO_2 emissions reductions and at the same time health, comfort, and safety.

The focus on air humidification was decided based on the performed Pareto analysis of all hospital steam consumers of the case study, as well as conclusions drawn from the literature study. According to the literature study and experts' opinions, no conclusive evidence was found that setting the humidification to off would increase infection spread risk to the user's health; however, for the thermal comfort of staff and long-stay patients, maintaining air relative humidity within determined range is advisable.

After the conducted research on the case study the recommendation is to verify for each building which AHUs supply treated air to critical healthcare functions as operating rooms, isolation rooms and intensive care units. On the buildings which do not have such functions, this study concludes that air humidification is not essential, and the determined ranges of RH could be achieved with alternative solutions.

In 4 out of 7 scenarios, the reduction in energy use and CO_2 emissions was over 75%, when compared to the current energy demand for humidification.

The 5-step method combined with a Pareto analysis to identify the main contributors to the overall CO_2 emissions and energy consumption and the Kesselring method to evaluate possible scenarios, were used to develop a generic strategy that can be applied in different hospital cases where humidification is applied with or without a central steam system, to achieve significant energy reductions and to accelerate the path to nZEB hospital buildings.

7. Acknowledgement

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The datasets generated during and/or analysed during the current study are available in the TU/e repository, https://research.tue.nl/en/studentTheses/towards-zero-energy-hospital-buildings-2