Analysis of Decentralised Air Humidification Systems for the UMCG

Bachelor Integration Project

Industrial Engineering and Management, Faculty of Science and Engineering

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Management Summary

The main goals of this study are, to provide insights into the standpoints of other hospitals with regards to adiabatic humidification, to create insights into the operational costs and resource usage of air humidification systems and to create an inventorisation of guidelines and regulations for humidification systems applicable to the UMCG.

It was found during this study that most hospitals showed interest in adiabatic humidification systems. When hospitals indicated they were hesitant towards this new humidification methods this was mainly due concerns regarding the microbiological safety. It was found during this study that the main factor for not using adiabatic humidification was the standpoint of Infection Prevention.

For the guidelines and regulations it was found that there are only few guidelines and/or regulations for hospitals within the Netherlands. Especially with regards to whether or not adiabatic humidification is allowed, most of them were lacking specific guidance.

The Arbowet 4.87b does allow for air humidification methods than steam humidification, but gives the requirement of performing a risk assessment & evaluation in case any other method than steam humidification is used.

With regards to the safety of adiabatic humidification it was found that guidelines from countries and hospitals were conflicting and had different point of views.

In America, the ASHRAE has approved the use of adiabatic humidification systems in hospitals in 2017. In Germany adiabatic humidification systems are also allowed in hospitals with the exception of operating rooms, where steam humidification is required. The Deventer Ziekenhuis, who uses an adiabatic humidifier in their operating room, noted that operating rooms are particularly interesting areas to use adiabatic humidifiers as the air is filtered by a HEPA-filter before entering the room. Therefore, in the off case that Legionella does form, has reached levels that can affect people and is not captured early by measurements, it will be filtered out of the air stream before entering the room.

It was also shown that the adiabatic cooling effect, with desiccant wheels, reflects an approximate maximum temperature change of 4.6 °C. Since the room temperature setpoint is 21 °C, the overall temperature stays relatively low if adiabatic humidification is used, but only if desiccant wheels are used.

It was also determined that the gas powered steam systems the UMCG accounted for an estimated 15.1% of the total gas consumed by the UMCG in 2022. Transitioning towards electric steam and adiabatic humidification would result in approximate sav-

ings of 1,000,000 m^3 of gas. Not only would this result in a significant reduction of total gas consumption but also in notable cost savings. It was estimated that the UMCG had a total operational expense of € 1,700,000 for air humidification in 2022. Switching to electric steam and adiabatic humidification systems would result in operational cost savings of € 500,000. When in addition to this transition, also installing desiccant wheels in all air handling units, these savings would increase by € 700,000, resulting in a total operational cost savings of € 1,200,000 per year with respect to a total € 1,700,000 being spend on air humidification in 2022.

Transitioning towards decentralised air humidification will not only result in a reduction of total gas consumption and reduced operational costs. It was also found that electric steam and adiabatic humidification would result in a reduction 28.7% and 34.3% in terms of energy and that electric steam humidification would also result in water savings of 15.0%.

It was also established that the centralised steam generation is well measured and accounted for a substantial part of the total resources used for humidification. When moving towards decentralised methods of air humidification, the resources will shift towards these decentralised locations as well. Therefore, it is proposed to in addition to this shift towards decentralised humidification systems to also start measuring the performance of the humidification systems within the air handling units.

And lastly, a five step process is proposed that can help the UMCG in reducing the resources used for humidification to improve sustainability.

1. Utilise desiccant wheels were possible.
2. Reduce humidification areas to where strictly requires/desirable.
3. Reduce level to which is humidified.
4. Use adiabatic humidification systems where possible, if, and where, allowed by infection prevention
5. Use decentralised electric steam humidifiers

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List of Abbreviations

AHS Adiabatic Humidification System

AHU Air Handling Unit

Amsterdam UMC Amsterdam University Medical Centre, location VUmc

ATES Aquifer Thermal Energy Storage, WKO in Dutch

CFU Colony-Forming Unit

DZ Deventer Ziekenhuis

Erasmus MC Erasmus Medical Centre

ESHS Electric Steam Humidification System

EZT Elisabeth-TweeSteden Hospital

GPSHS Gas Powered Steam Humidification System

HVAC Heating, Ventilation and Air Conditioning

ICU Intensive Care Unit

KNMI Royal Netherlands Meteorological Institute

LUMC Leiden University Medical Centre

MUMC Maastricht University Medical Centre

OR Operating Room

RAE Risk Assessment & Evaluation

RHDHV Royal Haskoning DHV

RO Reverse Osmosis

TCO Total Cost of Ownership

TNO Netherlands Organisation for Applied Scientific Research

UMCG University Medical Centre Groningen

Chapter 1

Introduction

The University Medical Centre Groningen (UMCG) is currently in the process of a hospital-wide expansion and renovation process, “UMCG bouwt” (UMCG builds). This is a multiyear project that is planned to be finalised by 2035. As part of this project, the air humidification systems will be renewed. The main goals of this project are to modernise and increase the sustainability of the UMCG. The sustainability is focused around the reduction of the CO_2 emissions and the consumption of natural gas.

At this time the UMCG buildings are humidified via a central steam network. This steam is generated at a central location where water is heated to 100°C using gas. For new buildings or large renovations, within the UMCG bouwt project, the UMCG is exploring new, decentralised, air humidification systems to reduce the consumption of gas. In addition, due to the recent gas price developments, the energy, gas and electricity bill of the UMCG of August is around 9 times higher compared to the same month a year earlier. Furthermore, the ongoing Covid-19 pandemic highlighted the importance of air humidification, as it was one of the main recommendations of the Dutch government to bring down infection numbers [1].

Therefore, shifting towards more sustainable air humidification systems within the UMCG will contribute to UMCGs objective of increasing sustainability and will, in addition, also result in reduced operating expenses due to a reduced gas consumption.

The norm for air humidification within hospitals has always been steam-powered humidification systems. However, due to recent developments, the quality of adiabatic humidification systems, where heat from the surrounding is used to evaporate water, have improved [2] and the ASHRAE, the leading organisation that maintains standards regarding hospital air conditioning in the United States, has approved the use of adiabatic humidification systems in 2017. Several renowned brands that provide hospital air humidification systems, such as Carel and Condair, have developed adiabatic systems that are specifically designed to satisfy the higher quality demands of hospitals [3, 4].

This study will contribute to the literature by assessing the new humidification systems, with regards to a hospital setting, by looking at them from a hygienic viewpoint and will assess the associated operational costs of the systems by developing a model that estimates the gas, water and electricity used by Gas Powered Steam Humidification Systems (GPSHSs), Electric Steam Humidification Systems (ESHSs) and Adiabatic Humidification Systems (AHSs), and then estimates the costs associated to these resources. Whereafter the financial implications of moving to decentralised systems will be discussed.

This report begins with a problem analysis, section 2.1, which will set out the problem context and expand upon the stakeholders involved, the description of the problem and the goal of the study. After that, in section 2.2, the research questions will be outlined and the methods, tools and operationalisation and validation will be discussed. This section concludes with the deliverable, the limitations and risks of the study. Then, chapter 3, will list all findings of this study with regards to theory, section 3.1, an inventorisation of hospital and expert standpoints, section 3.2, the developed model and the results from the model, section 3.3 and lastly the relevant regulations are listed in section 3.4. Next, in chapter 4 all the results will be put into context and finally chapter 5 will give answers to the research questions.

Chapter 2

Methods and Tools

2.1 Problem Analysis

2.1.1 Problem Context

Air humidity has an effect on several aspects, of which some are relevant in the context of hospitals and their patients. An outline of these aspects will be given in this section.

Health

There are several health implications with respect to the humidity or humidification of air. These implications can be categorised into three groups:

- protection
- contamination
- stress

These groups are combined from several papers that mention either one or several of these categories. Comfort is listed as a factor in [2, 3, 5, 6, 7, 8]; The reduced effectiveness of viruses and bacteria and reduced risk of electric discharges, i.e. protection in [3, 5, 8, 9]. and contamination, in particular with respect to legionella, in [2, 3, 6].

Each of these groups will be explained and expanded upon below.

Protection refers to the fact that the humidity levels can protect the patient against certain risks.

The spread of viruses and bacteria is highly dependent on the air humidification levels of the surrounding air. Consequently, proper air humidification can decrease the chance of infection of individuals. On the other hand, too high levels of air humidity will result in an environment were bacteria and fungus can thrive [10]. These viruses and bacteria are direct health risks, especially for hospital patients. Their immune systems are often weaker than average due to surgery or sickness. As a result, they are more likely to experience serious health implications when they are infected. To reduce the risk of infections the humidity should be kept between 40%-60% [11][1], except if circumstances require otherwise, such as when treating burn victims where higher humidity levels are desirable.

Furthermore, low air humidity levels also increase the chance of electrostatic discharges [10]. This phenomenon can be categorised under both protection and stress. Under protection would be where a surgeon receives an electric discharge upon performing a procedure on a patient. Under stress would be a patient receiving an electric discharge, which can increase their stress levels.

Contamination refers to the fact that air humidification systems introduce undesired particles into the air as a side effect of introducing water vapour, i.e. humidity, into the air.

This implication refers to a possible reduction in air quality if the medium, water, is not sufficiently clean. Any minerals or contaminants that are in the water when entering the air will also be introduced into the air [5]. These minerals and contaminants can result in a lowered air quality and the possible spread of bacteria via the humidification system. In particular, in Operating Rooms (ORs) and Intensive Care Units (ICUs), these contaminants pose a significantly larger risk during surgeries such as orthopaedic, implants, burned, cardiovascular surgeries and also in situations where the patient is immunocompromised [8]. Here it is of exceptional importance that the tools and the room have the particle amount under the threshold levels as given by regulations, ISO 14611-1, appendix A, such that contaminant particles do not form a health risk for patients.

In addition to this, with adiabatic air humidification there is also an increased risk of legionella forming due to still water [3]. Therefore, with an adiabatic system there are additional requirements to prevent the growth, and spreading, of legionella and other bacteria.

Humid air is also able to bind to dust particles better than dry air resulting in less accumulation of dust which also adds to a cleaner environment [9].

Stress refers to the additional stress in patients due to not being comfortable.

Air humidification levels can have a significant effect on patient comfortability. Low air humidity levels can result in respiratory problems; it can affect the eyes, skin and mouth, resulting in itchy eyes or skin and a dry mouth [5, 10, 12]. It can also cause a cold feeling [10]. High air humidity levels can result in heat strokes, especially for patients that have a weak heart [8, 10].

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[1] See appendix B for a visual overview of the effect of humidity with respect to several risk categories that are reduced at the ideal humidity range as found in [11].

Comfortable air can reduce additional physical and mental stress for patients which can have a positive effect on their recovery time [7].

Safety

Within a hospital setting, there is a great focus on safety of their used systems. ”Hospitals serve a uniquely vulnerable population exposed to an elevated risk of health, fire and safety hazards” [13]. Therefore, it is of exceptional importance that the new system is safe and in line with all regulations and demands of the UMCG. The UMCG has their own requirements, the Algemene Technische Bepalingen (general technical provisions) [14], which outlines all technical and safety requirements for systems used in UMCG.

Facility

At the UMCG there are several limitations that have to be taken into account with regards to the facility and regulations. The central steam network is currently gas powered and, therefore, not in line with the sustainability goals of the UMCG [4]. In addition there are also transport losses when the steam is transported to the respective locations. Therefore, the UMCG is now looking for decentralised options to reduce their gas consumption. Since hospitals typically operate 24/7, the new system must be carefully designed to allow for maintenance such that continuous operation is ensured.

Another important aspect that should be taken into account for air humidification systems within a health care setting are the regulations. In case of adiabatic humidification the Arbowet, article 4.87b [15], also requires a Risk Assessment & Evaluation (RAE). Hospitals are required to provide clean air and the concentrations of any contaminants must be below certain levels. Depending on the department within the hospital, these requirements can be more rigorous such as in ORs, ICUs and hospital laboratories.

Costs

There are multiple factors that determine the Total Cost of Ownership (TCO) of an air humidification system. The main factors determining the TCO are:

- Initial investment costs
- Maintenance costs
- Resource costs such as electricity, water and gas

Where the investment and maintenance costs for a system are relatively constant over time. The energy costs, especially in the last few years, have seen significant price fluctuations however. The current energy crisis of 2022 has had significant effects on hospital utility bills. The UMCG has experienced an increase of 800% in August in comparison to August a year earlier, and it is therefore important that the new system is chosen with these fluctuating and high gas prices in mind.

Additionally, hospital systems are often owner occupied for extensive time periods. It is estimated by the UMCG that the new system will operate approximately 20 to 25 years. Therefore, maintenance costs are an important factor as expensive and/or frequent maintenance costs can add up throughout the years. Consequently, the new system should be of high quality such that maintenance costs can be kept low.

Another issue with the investment and maintenance costs is that these differ significantly between each type of system and also depend significantly on the size of the system. Therefore, it is hard to decide which one is optimal as currently there is no easy way to determine these costs.

Insufficient air humidity can also cause damage to the building itself. Low humidity can cause wooden floors to shrink, separate or warp and wallpapers can peel around its edges. At high humidity, there is a higher chance of rotting and mould forming [10]. Therefore, maintaining proper air humidity can result in lower costs in other fields.

Pilot

The UMCG is currently running a pilot where an adiabatic air humidification system is tested at the pregnancy centre. This is a new building at the northern part of the UMCG. Due to technical complications, this system has not yet been active. This humidification season, fall and winter 2022, will be the first time that this new system is operational. The system utilises an evaporative adiabatic humidifier from HygroTemp, the EVA-pack, that is specifically made to comply with hospital regulations. Section 2.1.2 will expand on evaporative adiabatic humidifiers.

The intend of the pilot is to:

- Test if this adiabatic system can sufficiently humidify the air
- Create a microbiological assessment of the system by taking samples and analysing these in the laboratory.

Performance Indicators

Air humidification systems are dependent on, and have an influence on several other parameters. There are also several other important system indicators with regards to regulations and safety, these are included within the relevant regulations. The performance that are indicators listed below are with regards to the real time performance of the humidification system.

Accuracy To what extent the system is able to go to and keep the humidity at a given level or range.

Energy usage How much energy the system consumes, preferably measured in the amount of energy required per gram or kilogram humidified.

Speed How fast the new system is able to increase the humidity.

Air flow rate The volumetric flow rate of the air supplied to the room.

Area/volume The amount of area or volume covered by the system.

Temperature The temperature increase/decrease caused by the air humidification system, in particular for AHSs[2]

Air quality The effect of the system on air quality.

Medium

There are different options with regards to the medium that can be used to humidify the air [4]. These are, from cheaper to more expensive:

Tap water The hardness of tap water in Groningen is about 8 dH, which means it contains some chalk which deposits against the walls of the humidifier during the evaporation. Therefore, this medium requires significant more maintenance and is therefore not an option at UMCG.

Softened water Softened water is generally seen as hygienically unreliable. This is due to the resin being a breeding ground for bacteria. This results in the requirement of performing periodical microbiological assessments and to disinfect the softener at least yearly.

Reverse Osmosis water This medium has the benefit that there is almost no deposition of chalk or other minerals onto the humidifiers. This medium however has the disadvantage that it is expensive and requires more electricity. The current capacity at the UMCG to generate Reverse Osmosis (RO) water is also not sufficient if used for humidification. The use of this medium would therefore require dedicated RO installations. In addition it is also unclear whether the existing installations can be used for humidification since they are currently used only for medical applications.

With this the two options that are under consideration are softened and RO water.

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[2] An increase of 1°C in air temperature results in the air being able to hold 7% more water vapour. Thus a 6.5% drop in relative humidity. Whereas a decrease of 1°C results in a 7% increase in relative humidity

Other Hospitals

Several other hospitals and medical centre have recently investigated the use of or are already using adiabatic humidification systems in their facilities.

Deventer Ziekenhuis In 2016 Deventer Ziekenhuis (DZ) started the development of a hybrid OR. Due to a steam shortage at DZ they investigated the use of an adiabatic system. They decided to utilise the Condair DL hyrbid humidifier which has received certification, guaranteeing 100% hygiene [16]. So far the use of this adiabatic system has not introduced any issues or safety concerns.

Leiden University Medical Centre Is currently not shifting towards adiabatic humidification systems. The main reason to postpone the use of adiabatic systems within the Leiden University Medical Centre (LUMC) is due to the absence of positive advice from the hygienists of the LUMC.

Erasmus Medical Centre The Erasmus Medical Centre (Erasmus MC) is currently in the orienting phase and has commissioned TNO to study the effect of air-technical and micro-bacterial differences between adiabatic and steam based systems. Based on the results of this study they will decide whether they will shift to adiabatic humidification. In the meantime they are reducing the number of humidified rooms that do not require humidification in line with an earlier study performed by TNO, which investigated the need of humidification within hospital and in which areas it is necessary to humidify [2].

Maastricht University Medical Centre The Maastricht University Medical Centre (MUMC) has made the decision to shift towards using adiabatic humidification.

2.1.2 System Analysis

Most air humidification systems rely on a physical process to provide water vapour to humidify air. These two processes are isothermal and adiabatic humidification.

Isothermal humidification is a process in which boiling water is the main source of energy. The primary method of isothermal humidification is vaporisation. Vaporisation is a process in which boiling water is used to generate steam, which is then directly injected into the air [17]. The generation of steam can be performed in either a central location or be distributed over multiple decentralised locations. To provide the energy to generate the steam via boiling water, either electricity or gas can be used. The steam that is generated can be directly injected into the air in an Air Handling Unit (AHU). During this injection the temperature of the air remains essentially the same. Hence, the name isothermal humidification.

Adiabatic humidification is a process in which the surrounding air is the main source of energy. The water is provided to the air in liquid form and must still achieve its gaseous state. The energy required for this process is drawn from the air in the form of heat [18]. Since this process reduces the air temperature this will also have an effect on the relative humidity, see appendix C for the approximated effect of a 1°C change on relative humidity. Adiabatic humidification generally involves a wetted medium (evaporation) or a spray/nozzle mechanism (atomisation). A by-effect of adiabatic humidification is that the surrounding air is cooled due to that heat from the air is used. Depending on the setting and the interconnection with the other Heating, Ventilation and Air Conditioning (HVAC) systems, this can be favourable or unfavourable. Since the UMCG uses their humidification systems in the August-March period, when the outside air is cooler than the inside air, this will result in additional costs required for heating the air. This increase in heating costs must also be taken into account.

The UMCG currently uses a centralised system to humidify the air. It would be possible to renovate this system such that it becomes more efficient. The scope of this study, however will be on decentralised systems as the potential for energy and costs savings is larger.

For a graphical overview of the isothermal and adiabatic processes and their most common methods, please refer to figure 2.1.

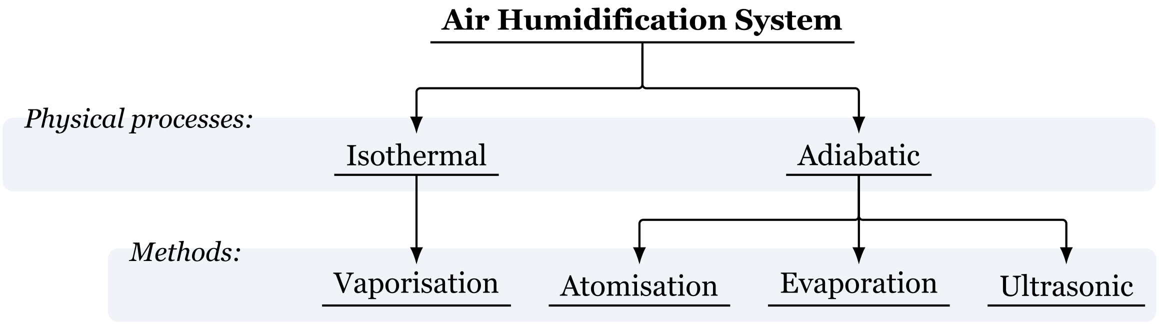

Figure 2.1: Overview of the main air humidification systems

2.1.3 Conceptual Model

To clarify the problem a 5W2H analysis is performed. This analysis method can be used to either describe the problem or to describe a solution. In this case it is used to describe the problem.

What is the problem? The air humidification system is not aligned with the UMCG sustainability goals

Why is that a problem? The UMCG wants to reduce their CO_2 emissions and gas usage

Where do we see this? i.a. In the emissions/dependency on gas of the humidification systems

Who suffers? The UMCG

When was this first observed? When the new CO_2 reduction goals had been set by the UMCG

How does this happen? The air humidification system is gas powered

How much does this cost? To give an indication, in August of 2022 the gas powered systems were around 9 times more expensive than August the year before.

2.1.4 Stakeholder Analysis

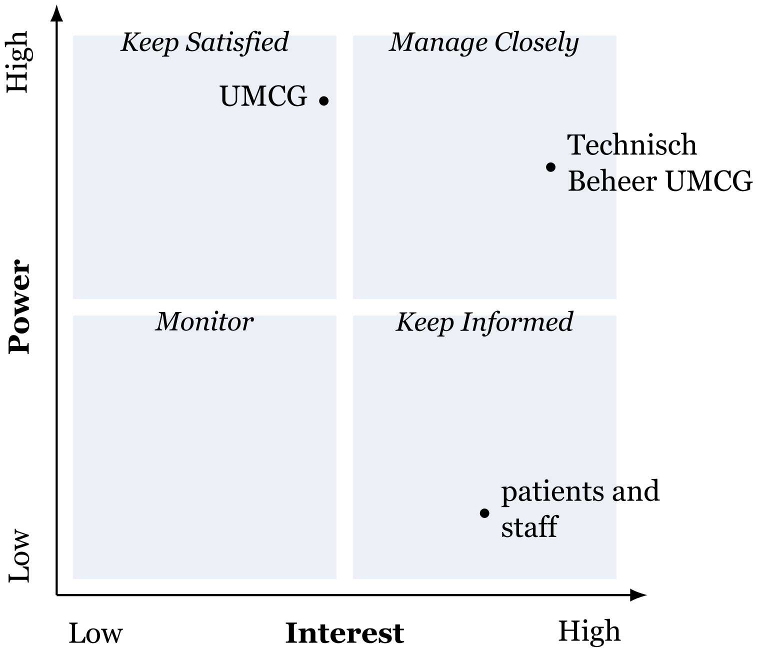

Figure 2.2: Identified stakeholders mapped to the power/interest grid

The problem owner in this research project is the UMCG Building and Facility – Technical Services department. They are the main problem owner and have a high interest, as this research project will help them develop an air humidification system for their facilities. They also have high power, as ultimately they are responsible for developing this new system.

Another stakeholder is the upper management of the UMCG. They have the highest power, as they direct the building and facility department. Their interest, however, is medium since there already is a working air humidification system and it is not one of their main priorities. They should, however, be kept informed of the overall developments within the building and facility department.

The last group of stakeholders are the patients, visitors and staff that will be in the facilities where the new air humidification system will be utilised. Their main interest is that the new system is safe and if and how it will affect them. Their power is low, as individuals, however, as a group they are able to influence the upper management of the UMCG. Therefore, it is important to develop the new air humidification system in close collaboration with this stakeholder group.

2.1.5 Problem Statement

The UMCG is assessing whether they want to replace their current centralised humidification system with a decentralised system. It is currently unclear to the UMCG whether or not adiabatic systems can be used, and if so, in what departments these can be used. Therefore, they want to know what methods are suitable for the different departments taking into account standardisation throughout the hospital to reduce downtime. In addition the UMCG is not certain whether this would ultimately lead to a lower TCO.

2.1.6 Goal Statement

To contribute to the design of a decentralised air humidification system at the UMCG that has a satisfactory TCO and satisfies all regulatory and UMCG specific requirements by analysing the available market solutions with regards to the quality, functional and regulatory requirements and the associated costs with regards to investment and operational costs before January 20, 2023.

2.2 Research Design

2.2.1 Methodology

The overall approach in this study will be a multi-criteria analysis. The decentralised systems will be analysed using several criteria across several disciplines. This will be used to create an overview of feasible options for the UMCG and to give an indication of the TCO per option.

Within the engineering cycle this study will focus on the problem investigation, treatment design and treatment validation. A particular importance is on the treatment validation due to the significant number of regulatory requirements at the UMCG.

2.2.2 Research Questions

How can a new decentralised humidification system be selected that satisfies the requirements and demands of the UMCG?

- What are the requirements and guidelines for air humidification systems within a health care facility setting, regulatory and customer specific?
- What are the costs associated with the different types of humidification systems, i.e. GPSHSs, ESHSs and AHSs?
- How much resources are used by the different humidification systems with regards to gas, electricity and water?
- What are the available options to evaluate the performance and resource usage of an air humidification system?

2.2.3 Methods, Tools and Operationalisation

To answer these research questions, information has to be collected using available tools and methods. In this study, mainly literate research will be used as a tool. In addition, interviews with experts will be utilised to gain more in-depth information about the specific requirements of and, potential, systems at, the UMCG. Additionally, a theoretical model will be used to create insights into the operational costs of different humidification systems.

Humidity will be measured as relative humidity[3] which takes into account the current air temperature. By using the relative humidity, the system will aim to have the optimal humidity at that temperatures.

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[3] Relative humidity is the percentage of water vapour currently in the air compared to the maximum amount of water vapour that air can hold at that temperature

Performance of an air humidification system will be with regards to what extent it can keep the humidity in a given room at the desired value or range and how accurately it can control the humidity, in percentages.

Resource usage of an air humidification system will be with regards to the amount of electricity, gas and RO water used by the system.

Decentralised humidification system will refer to any humidification system which does not require steam from a central location other than the AHU itself and is not powered by gas.

Centralised humidification system will refer to any humidification system which requires steam from a central location other than the AHU itself.

These last two definitions ensure that the following cases are all considered to be decentralised:

- Electric steam humidification within the room.
- Electric steam humidifier placed within the AHU.
- Adiabatic humidifier placed within the AHU.

2.2.4 Validation

There are five criteria to validate a literature review [19]. These are purpose, scope, authority, audience and format. For a proper literature review, these should have all been taken into account during the whole process.

Within the engineering cycle, validation refers to the fact that before implementation it is justified that the treatment will indeed contribute to the stakeholder goals.

External validation has already proven to be quite difficult as the DZ is currently utilising adiabatic systems without any problems, MUMC have decided to start using adiabatic systems, Erasmus MC is still not sure and awaiting research results and LUMC will not use adiabatic systems yet due to the lack of a positive advise from its hygienists. Thus, it can be seen that apparently there are factors outside of the humidification systems itself that determine whether these systems can be used. Therefore, it is important to know that what works for one hospital, does not have to work for another hospital.

2.2.5 Deliverable

The final deliverable will consist of the findings of the literate research performed in this study and the developed model for the operational costs. This will include an overview of the humidification methods and solutions currently available with an assessment of the associated operational costs and operational factors such as the controllability of the system.

2.2.6 Limits/Risk Analysis

The information used for energy usage and investment costs are generally given by the manufacturer. These tend to be more optimistic than what will be seen in real-life cases, as the circumstances will be less ideal than used in the test setting. In addition, costs are inherently variable due to factors such as inflation and change in electricity prices. Next to that, investment costs are also dependent on the size of the system, the location of the system within the building and the location of the building itself. Therefore, the actual investment and operational costs can differ from estimations.

Some information is also not quantified and is only given in qualitative form, such as the terms *expensive* and *inexpensive* . Quantifying this information via experiments can be very time consuming and also expensive and, therefore, not possible during this study. This study will therefore quantify this information via reasoning and using literature to make educated assessments. This can result in inaccuracies.

Chapter 3

Results

In this chapter the results from the literature research and interviews with hospitals and experts will be presented. Section 3.1 will present a theoretical basis for calculations on concepts relevant to air humidification systems. Section 3.2 will present the results from the interviews with hospitals and experts. From the results of these interviews, section 3.3 will present a theoretical model for assessing the operating costs of different humidification systems and lastly, section 3.4 will present the regulations and standards that are applicable to the UMCG.

3.1 Concepts

3.1.1 Gas laws

Law of Partial Pressures

The atmospheric pressure can be dissected into the partial pressures that each gas in the air exerts. This can be done by using Dalton's law of partial pressures.

Dalton's law of partial pressures states that the pressure of a mixture of gases is equal to the sum of the partial pressure that each individual gas would exert by itself at the same volume and temperature.

$$p_t = p_1 + p_2 + p_3, \tag{3.1}$$

where p_t is the total pressure of the mixture of gases and p_1, p_2, p_3 are the partial pressures of the individual gases.

Using Dalton's law of partial pressure, the atmospheric pressure (p_{at}) can be dissected into the pressure of dry air (p_a) and the pressure of water vapour (p_s), note that further in this report, unless stated otherwise, the subscript a or da will be used to indicate a dry air property and the subscript s to indicate a water vapour property:

$$p_{at} = p_a + p_s \tag{3.2}$$

This relationship between atmospheric pressure and air and water vapour pressure is used in several calculations in this report to calculate the pressure of the air component when the atmospheric and water vapour pressure are known.

General Gas Law

Boyle's law states that, at constant temperature, the product of the pressure p and volume V of a gas remain constant [20], i.e.

$$pV = \text{constant} \tag{3.3}$$

Charles's law states that the volume a gas V is proportional to its absolute temperature T, the pressure remaining constant [20], i.e.

$$V/T = \text{constant} \tag{3.4}$$

Combining Boyle's and Charles's law gives the general gas law [20]

$$pV = mRT, \tag{3.5}$$

where R is the gas constant for a particular gas given by

$$R = \frac{R_0}{m}, \tag{3.6}$$

where R_0 is the general gas constant in J/mol K, and m the molecular mass of the gas in kg/mol.

In the following section, equation 3.5 will be rewritten to the form of mass over volume, m/V, which will form the definition of the absolute humidity of water vapour.

Equation 3.6 will be used to calculate the specific gas constant of air R_a and water vapour R_s.

3.1.2 Definitions

There exist two definitions of absolute humidity, one as often given in research, and another definition of absolute humidity is actually that of moisture content. For practical reasons, the latter definition is often used in hospital engineering departments as it is unaffected by temperature. It is important to note this distinction between definitions. Within this report, absolute humidity will be distinctly defined from moisture content.

Vapour pressure (p_s) is defined as the pressure that is exerted by water vapour in Pa [20].

Saturation vapour pressure (p_{ss}) is defined as the pressure exerted by water, which is in equilibrium between its liquid and gas state for a certain temperature T, in Pa. Since there is no simple relationship between temperature and SVP an approximation must be used [20]. In this study the Arden-Buck approximation is used

$$p_{ss} = 611\,211 \cdot \exp\left(\left(18.678 - \frac{T}{234.5}\right)\left(\frac{T}{257.14 + T}\right)\right) \tag{3.7}$$

Relative humidity (φ) is defined as the percentage ratio of vapour pressure of water vapour in the air to the saturated vapour pressure [20, 21, 22].

$$\varphi = \frac{p_s}{p_{ss}} \times 100\% \tag{3.8}$$

Absolute humidity (ρ) is defined as the mass of water vapour present in 1 cubic meter, in kg/m^3 [21, 22]. It is also referred to as the *density* [20].

$$\rho = C\frac{p_s}{T}, \tag{3.9}$$

where C is defined as $\frac{1}{R_s}$ and the temperature T in Kelvin.

Moisture content (g) is defined as the mass of water vapour present in 1 kg of dry air, in kg/kg$_{\text{da}}$ [20]. It is also referred to as the *mixing ratio* [21, 22].

$$g = \frac{m_s}{m_a} = \frac{R_a p_s}{R_s p_a} = \frac{R_a p_s}{R_s\left(p_{at} - p_s\right)} \tag{3.10}$$

Saturation moisture content (g_{ss}) is defined as the moisture content when the vapour pressure p_s is at the saturated vapour pressure SVP (p_{ss}), in kg/kg$_{\text{da}}$ [20].

Percentage saturation (μ) is defined as the percentage ratio of moisture content in the air to the moisture content at saturation at the same temperature [20].

$$\mu = \frac{g}{g_{ss}} \times 100\% \tag{3.11}$$

Specific volume (v) is defined as the volume of air containing 1 kg of dry air plus the associated moisture content, in m^3/kg [20]. It is derived from the general gas law, equation 3.5.

$$v = \frac{V_a}{m_a} = \frac{R_a T_a}{p_a} = \frac{R_a T_a}{p_{at} - p_s}, \tag{3.12}$$

where T_a is the dry bulb temperature of air in Kelvin

Specific humidity (q) is defined as the mass of water vapour per the total mass of air, in kg/kg [21].

$$q = \frac{g}{1+g} \tag{3.13}$$

Enthalpy (h) is defined as the internal energy of a system plus the product of pressure and volume, in J [23]

$$h = u + pV, \tag{3.14}$$

where u is the specific energy in J, p is the pressure in Pa and V is the volume in m^3.

Dry bulb temperature (t) is the temperature of air obtained with a thermometer which is freely exposed to the air but shielded from radiation and free from moisture, in °C [20].

Wet bulb temperature (t') is the temperature of air obtained with a thermometer whose bulb is covered by a sleeve that is kept moist with water, freely exposed to the air and free form radiation, in °C [20].

Heat content (Q) is defined as the amount of energy required to heat a given substance from a certain temperature to a new temperature, in J [24].

$$Q = mc\Delta T, \tag{3.15}$$

where m is the mass of the substance in kg, c is the specific heat capacity of the given substance in J/kg°C and ΔT is the temperature difference in degrees Celsius.

A note to the above definitions, the relative humidity and saturation ratio are not identical. They are, however, very close in numerical value. They are usually considered to be interchangeable [21].

Using equation 3.6 the specific gas constants for dry air and water vapour can be derived. The obtained values can be found in table 3.1.

Given a certain moisture content g, equation 3.10 can be rewritten to obtain the vapour pressure

$$p_s = \frac{gR_s p_{at}}{R_a + gR_s} \tag{3.16}$$

3.1.3 Procedures

Some of the measures of moisture, relative humidity, moisture content and absolute humidity, have to be converted to one another. The following two calculation procedures will be used in the models that are developed in section 3.3.7 and section 3.3.8.

Table 3.1: Calculated gas constants and general constants R_0, M_a, M_s.

	Description	Unit	Value	Source
R_0	Universal gas constant	J/mol K	8.31446	
M_a	Mass dry air	g/mol	28.97	[20]
M_s	Mass water vapour	g/mol	18.02	[20]
R_a	Gas constant dry air	J/kg K	287.0	
R_s	Gas constant water vapour	J/kg K	461.4	

To calculate the moisture content, given a temperature and relative humidity, first the saturation vapour pressure must be calculated, using equation 3.7. From this the actual vapour pressure can be determined, given that the relative humidity is known. With this the moisture content can be determined using equation 3.9.

To calculate relative humidity, given a temperature and moisture content. First, the saturation vapour pressure must be calculated, using 3.7. Using equation 3.9 the actual vapour pressure can be calculated. With the vapour pressure and saturation vapour pressure known, the relative humidity can be calculated using equation 3.8.

3.2 Experiences of Other Hospitals and Experts

Interviews with several hospitals have been conducted. These are with the Deventer Ziekenhuis (DZ), Erasmus Medical Centre (Erasmus MC), Elisabeth-TweeSteden Hospital (EZT), Maastricht University Medical Centre (MUMC) and the Amsterdam University Medical Centre, location VUmc (Amsterdam UMC).

An interview has also been conducted with HygroTemp, the supplier of the AHS used in the pilot of the UMCG.

In addition, interviews with the research organisations Netherlands Organisation for Applied Scientific Research (TNO) and Royal Haskoning DHV (RHDHV) have been conducted.

The findings of the conducted interviews are divided into the following sections

- Inventarisation of Adiabatic Humidification Systems
- Periodic Testing of Microbiological Contaminants
- Energy and Water Performance
- Renovation vs Construction
- Relevance of Humidification

3.2.1 Inventarisation of Adiabatic Humidification Systems

An overview of the adiabatic systems used by the hospitals that were interviewed can be found in table 3.2. It was determined that most hospitals utilised desiccant wheels, only the Erasmus MC has indicated they do not utilise desiccant wheels due to a lack of evidence these systems are, in fact, hygienically safe.

Table 3.2: Adiabatic humidification systems used in hospitals.

Hospital	System(s)	Supplier(s)
UMCG	EvaPack	HygroTemp/Armstrong
DZ	Condair DL	Condair
Amsterdam UMC	?	Condair, Carel
EZT	EvaPack	HygroTemp/Armstrong
MUMC	-	-
Erasmus MC	-	-

3.2.2 Periodic Testing of Microbiological Contaminants

In some countries, regulations apply that require for periodic testing for Colony-Forming Units (CFUs) of Legionella in air humidification systems. In the Netherlands, this is regulated by the Arbowet, article 4.87b [15], which states that for adiabatic systems yearly tests are required to ascertain that the number of CFUs is below the maximum allowed value of 100. In practice, hospitals must already perform periodic tests for Legionella on other systems and these adiabatic systems are simply included in the existing schemes. At the DZ and Amsterdam UMC these are often already planned at more frequent intervals than what is required by the Arbowet for adiabatic humidification. The Amsterdam UMC performs monthly tests since it is new system.

Both the DZ and Amsterdam UMC are satisfied with the performance of their humidification systems with regards to the number of CFUs. The DZ has observed a slight elevation in CFUs only once, which did not pose any risks to the spread of Legionalla within the hospital, but did require a full rinsing of the humidification system. The Amsterdam UMC has not experienced an elevation that risked exceeding the maximum allowed number of CFUs.

Also in the interview with HygroTemp it was mentioned that their system was VDI 6022 certified. The VDI 6022 is a set of guidelines that aims to prevent the growth of Legionella. The Amsterdam UMC also indicated that this was a guideline they used in the design and selection of their air humidification systems. As pointed out by the Erasmus MC, the VDI 6022 only provides guidelines on preventing the growth of Legionella. In contrast to steam, which kills Legionella by boiling the water, a VDI 6022 certified system is only designed to not be a feeding ground for the growth of Legionella.

Another guideline mentioned by the UMCG is the ISSO 55.1, which is a manual for the prevention of Legionella in water aimed at hospitals. This manual also proposes steps that can be followed to prevent the growth of Legionella. This guideline does however also not guarantee that the system is 100% safe.

3.2.3 Energy and Water Performance

The performance of the air humidification system at the DZ, Amsterdam UMC, UMCG, MUMC and EZT was only measured with regards to the accuracy of the air humidity and air temperature. There were no measurements of the energy and water consumption of these specific systems. Therefore, at this moment these hospitals could not provide any insights into the costs or cost efficiency of their systems. The EZT did aim to measure the water loss of the adiabatic humidifier used in their pilot as they noticed a significant water loss. This measurement showed an approximate water loss of 30% RO water.

At the time of the interview it was not yet determined what the source of this water loss was. The humidification system that was used advertised a 100% effective water use, but under the circumstances of the EZT this was not the case.

Since most hospitals indicated to not measure many paramaters regarding their humidification, it has yet to be determined whether measuring parameters relating to costs and efficiency at the UMCG is desirable to gain insights into energy efficiency of these systems. It should also be noted that therefore any cost calculations performed in this report will have a theoretical basis.

What was indicated by many hospitals and also by RHDHV, is that depending on the implementation of the adiabatic system to other systems, it can result in significant energy, and cost, savings. In the DZ they make use of a Aquifer Thermal Energy Storage, WKO in Dutch (ATES) system. Because of an inbalance between heat and cold demand during the seasons they observed an excess of heat, which they had to cool down. When installing the adiabatic system they connected this to the ATES system such that the adiabatic cooling effect of the humidification system was used to decrease cool down the excess heat.

The DZ also observed that their heating batteries in the AHU did not have the capacity to heat the air to offset the adiabatic cooling effect. They solved this by adding a changeover to the cooler battery. This changeover resulted in the DZ being able to use their cooler battery as a second heater battery.

The Erasmus MC also indicated that the costs of the AHS operating at DZ were used as cost indications by the supplier. The Erasmus MC noted on this that the costs that they would observe would not be similar to this due to the difference in heating costs.

The combination of connecting it to their ATES system resulted in cost reductions in both the humidification system and the ATES system. In the AHU the amount of heating required was reduced whereas in the ATES system the amount of energy for cooling the excess heat was reduced.

3.2.4 Renovation vs Construction

The pilot system of the UMCG is located within a temporary department and is in a new construction setting.

The adiabatic systems used in the ORs of the DZ have been placed in a new construction environment whereas the rest of the AHSs at the DZ have been placed in renovation settings.

The AHSs in the Amsterdam UMC have been placed in a construction setting for the imaging centre and in a renovation setting elsewhere.

The AHSs used at Erasmus MC has been placed in an area designated for teaching. This location is not intended for patients and therefore there are no concerns from the infection prevention department.

An overview of the setting of AHSs within these hospitals can be found in table 3.3.

Table 3.3: Overview of the settings in which the AHSs have been placed or in what setting the usage of adiabatic systems are investigated for future use. N.A. indicates there are no active plans to install adiabatic systems in construction/renovation

Hospital	Current	Future
UMCG	pilot	not sure
DZ	yes	N.A.
Amsterdam UMC	yes	N.A.
EZT	pilot	–
MUMC	no	–
Erasmus MC	no[1]	awaiting research outcomes

[1] They do make use of AHSs in several student education areas where there are no patients.

Especially in renovation settings it is important to take into account that the build in length of adiabatic systems tend to be longer than those of conventional steam systems. It is important to plan accordingly and to find solutions beforehand such that the adiabatic system can be installed.

It is also important to take into account the increased power consumption required for heating to offset the adiabatic cooling effect. The EZT found that installing the EvaPack resulted in an increased power consumption of 80kW.

3.2.5 Relevance of Humidification

From the interview with TNO it followed that many of the reasoning used to highlight the importance of maintaining correct humidity levels as given in section 2.1.1 are not all scientifically proven. Manufactures often tend to give these reasons to indicate the importance of maintaining correct humidity levels. They, however, often refer to scientific papers that have performed experiments under lab conditions. There are a very limited amount of scientific studies that only measure the effect of humidity in real-life environments. These studies are also limited in the fact that it is hard to get conclusive results as there are many variables that influence or might influence the behaviour of microbiological organisms and it is hard to control all of these in a real-life scenario.

An example that was discussed with the TNO is the Sterling Chart, appendix B. This is a study published in 1986 that aimed to describe the survivability of airborne transmitted infectious bacteria and viruses [25]. This study proposed the Sterling Chart that clearly describes the survivability of these organisms at different relative humidity levels. This study is limited in that it did measure in terms of infectability but only in terms of survivability. Because the survivability was measured it cannot be concluded that at humidities where they can survive better or longer that this also results in more infections.

In this interview it was also noted that many of the guidelines available in other countries, such as the ones developed by ASHRAE, are developed by experts and are, in part, created from experience and it is not clear to what extend they are based on scientific arguments.

The research performed by the TNO [26] elaborates on several other shortcomings of most scientific findings, these are

- The amount of ventilation significantly impacts the effect relative humidity might have on infectability of viruses.
- Infectability of viruses is dependent on much more than just relative humidity
- Studies involving itchy eyes, nose and skin and slight airway complaints are often for a limited duration, i.e. a few hours, whereas hospital patients are generally exposed to these conditions for an extended time, i.e. a few days.

From the interview with RHDHV more context was obtained on the dust binding ability of humid air. As mentioned in the problem context, section 2.1.1, humid air has the ability to bind to dust which results in less dust in the air. The RHDHV noted that this also has the drawback that if there are relatively cold smooth surfaces, such as glas windows, then the water vapour will condensate on these windows due to the large temperature difference with the outside air and the dust will stay behind on these surfaces. This can result in increased costs due to more frequent cleaning of the windows.

The MUMC has also indicated a strong desire to reduce the amount of humidification, they observed that in Scandinavian countries, that have similar winter conditions as the Netherlands but for a more extended period of time, most hospitals do not make use humidification. The Erasmus MC provided some additional context to this. The Erasmus MC noted that this is mostly due to the significant costs that would be experienced if they would humidify their rooms. Nevertheless, it can be argued that they did make the decision that the potential inconvenience for patients and staff was not worth the costs of humidifying.

The study of the TNO also has several findings that are relevant with respect to the relevance of humidification [26], a short list of some noticeable findings is listed here

- Relative small difference of activity SARS-CoV-2 between 20% and 70% relative humidity at 20°C.
- Aerosols produced by breathing, talking and coughing are reduced in size by evaporation, this effect stabilises at relative humidities below 70%.
- Sensitive medical equipment can observe problems at 30% relative humidity.

This study concluded by proposing a 30% lower limit for relative humidity with the note that it is still important to, find a balance between infection prevention, comfort of the user by taking into account the duration of exposure to the environment, the nature of the activity and the presence of sensitive medical equipment in room.

3.3 Cost Calculations

From the interviews with other hospitals it was discovered that there was a lack of insights into the resource utilisation of the AHUs. Most hospitals had no indication of resource usage of water and electricity for their humidification systems. This section presents a theoretical basis and the developed resource and cost models and will list the results of these models.

3.3.1 Electricity Costs

The UMCG has provided data regarding their monthly energy prices of 2022. These can be found in appendix D. In order to use these energy prices in the model that will be developed in section 3.3.8, the average price of electricity has to be determined. The UMCGs energy contract consists of peak and off-peak hours. The peak hours are from 08.00-20.00 on weekdays and off-peak hours are from 20.00-08.00 on weekdays and the entire weekend. In accordance with the UMCG, the intensity of the humidification systems is taken as 100% from 08.00-20.00 every day of the week and 50% from 20.00-08.00, also, every day of the week. An overview of this scheme is provided in table 3.4. Lastly, the humidification systems are primarily active during the humidification season. These the months jan-mar and oct-dec.

Table 3.4: Overview of energy rates during weekdays and weekends at the UMCG.

Time		Utilisation	Hours	Energy rate
08.00-20.00	week	100%	60	peak
20.00-08.00	week	50%	60	off-peak
08.00-20.00	weekend	100%	24	off-peak
20.00-08.00	weekend	50%	24	off-peak

In order to determine an average energy price, first, the average electricity price per month is calculated by calculating the weighted average of peak and off-peak hours during the week and the intensity of utilisation. This yields the following formula:

$$\text{average} = \frac{60\text{h} \cdot 100\% \cdot \text{peak} + ((60\text{h} + 24\text{h}) \cdot 50\%) + 24\text{h} \cdot 100\%) \cdot \text{off-peak}}{168\text{h}}, \tag{3.17}$$

where the peak and off-peak variables are the peak and off-peak electricity prices of the respective month and the weighted average is in € /MWh.

The average electricity prices calculated using equation 3.17 can be found in table 3.5.

Table 3.5: Average energy prices per MWh of the UMCG in the year 2022.

Jan	146.96	May	134.57	Sep	259.25
Feb	127.96	Jun	157.64	Oct	118.61
Mar	195.75	Jul	229.36	Nov	138.32
Apr	148.07	Aug	335.57	Dec	201.82

Next, to calculate an average electricity price over the year, the average is taken of all the months. Note that the difference in number of days per month is not taken into account in this calculation. This yields an average electricity price of € 182.82 per MWh for the entire year and an average electricity price of € 154.90 per MWh within the humidification season.

3.3.2 Reverse Osmosis Water Costs

The price estimations of reverse osmosis water fluctuate to some extent between different estimations, \$0.03 per gallon [27], \$0.0035 per gallon [28] and \$0.025 per gallon [29, 30], these price estimations are exempt of VAT and other taxes as there is no VAT on tap water for domestic customers in the US. Converting this to litres and euros[1] yields price estimations of € 0.00733, € 0.000875 and € 0.00666 per litre, respectively.

For reference, the water price in Groningen in 2022 was approximately € 0.00072 per litre, excluding 9% VAT and taxes [32], which implies that the price of reverse osmosis water is between 9 and 10 times higher than that of tap water. The estimation of [28] has not been taken into account as it can be observed this price is only 1.2 times the water price in Groningen, whereas [28] lists water losses for RO greater than 1.2, making this price an unrealistic estimation. Since this source does not provide additional insights into the estimation, it was decided to exclude this cost estimation in further calculations.

As noted, within a reverse osmosis system a substantial percentage of water is lost, estimations vary to some extend, but indications are given as 75% [33] and 80% [27, 30], whilst [29] notes that newer systems can have much better efficiency near 50%. These losses have already been taken into account in the estimations provided above.

A study from 2006 also found the following cost equation for RO plants in Egypt [34]

$$C_p = 6.25 Q_w^{-0.17}, \tag{3.18}$$

where C_p is the unit production cost in \$/m^3 and Q_w is the capacity expressed as flow rate in m^3/d.

Using the average RO water consumption of the UMCG from 2019 to 2021, table 3.6, yields a price of 0.00337 per m^3. Adjusting for inflation since 2006 and converting to euros yields, € 0.00481 per litre. It should be noted that the formula proposed by [34] is designed to give indications of costs for RO plants with a capacity between 250 and 50000 m^3/d. From table 3.6 it can be concluded that the UMCG does not fit into this category as daily capacity of RO water is only 37.79 m^3/d. This could explain the 50% difference with the estimations provided by [27, 29, 30].

It should be noted that all these estimations are rough indications and are, likely, not accurate for the Dutch market since prices of tap water and electricity differ per region and/or country. In addition, only [27, 30] give insights into how the estimations were derived. They state that RO water is roughly 5 times the price of tap water and only [31] elaborately explains in detail how the proposed formula was obtained, their proposed estimated cost would exclude any other costs such as maintenance and operational costs. To obtain a final price estimation of RO water, the average of the two

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[1] By taking into account the average currency exchange rate between the US dollar and the Euro in the publication month of the article, using [31]. Since all estimations were published in 2022, any inflation has not been taken into account

estimations [27, 30] and [34] is taken. This yields a final price of € 0.00627 per litre, which will be used as the estimated costs of RO water in this report.

3.3.3 Gas Powered Steam Humidification System Costs

The performance of the current steam systems at the UMCG have to be reported yearly in the UMCGs activity report. Appendix E shows the Excel sheet used by the UMCG to calculate the price per kWh used for steam. Their report consists of the amount of steam produced and all expenses relevant to this production, such as labour costs, maintenance costs, depreciation costs and personnel costs. Combining this with the amount of RO water used and using the estimated cost of RO water, an estimation of the costs per kg of steam can be made. Since the goal of this estimation of steam costs per kg is to provide a direct comparison with the costs of ESHSs and AHSs, which will be expanded upon later in this report, it is important that some costs are not included in these estimated cost per kg as they are not known or cannot be meaningfully estimated for ESHSs and AHSs. Therefore, the costs of maintenance, personnel, depreciation and interest have been excluded.

Table 3.6: Parameters measured by the UMCG as reported in the last three years with regards to the steam production.

Description	Unit	2019	2020	2021
Supplemented RO water	m^3	14406	13481	13497
Gross steam meter	kWh	19.972.000	20.400.000	18.842.000
Gross steam produced	kg	25.984.532	26.541.381	24.514.348

Using the data provided in the report of the UMCG, table 3.6, and setting the maintenance, personnel, depreciation and interest expenses to € 0 and setting the profit margin to 0% yields a price of € 0.1785 per kWh.

To calculate the price of 1 kg of steam, the total amount of energy, in kWh, used to generate the steam has to multiplied with the price of 1 kWh. Next, the price of 1 m^3 of RO water, as found in section 3.3.2, has to be multiplied with the gross amount of RO water used. Then, these two results can be added together and divided by the total amount of kilograms of steam produced. This will yield the estimated price per kilogram of steam. The following equation can be derived from the reasoning above:

$$\text{costs steam €/kg} = \frac{\text{cost energy/kWh} \times \text{gross steam meter (kWh)} + \text{costs RO water/m}^3 \times \text{gross RO water (m}^3\text{)}}{\text{gross steam produced (kg)}} \tag{3.19}$$

This yields prices of €0.14067, €0.14038, €0.14065 per kg of steam for the years 2019, 2020 and 2021, respectively. Resulting in an average cost of €0.14057 per kg steam.

3.3.4 Electric Steam Humidification System Costs

The amount of electricity required for electricity powered steam humidifiers can be calculated using equation 3.15, where m is the humidification load, c is the specific heat capacity of water, 4.186 kJ/kg°C [35] and ΔT is the temperature change from the input water. The average temperature of tap water in the Netherlands is around 10 °C [36].

Next, the water has to be transformed into steam. This requires a certain amount of energy known as the latent heat of vaporisation, 2256.4 kJ/kg at 100°C [37]. Thus, the total energy required for electric steam humidification is given by

$$Q = mc\Delta T + mL \tag{3.20}$$

From this it follows that a total energy of 2633.14 kJ or equivalently 0.7314 kWh, per kilogram is required when an electric steam boiler is used. This calculation does not take into account energy efficiency or energy/transportation losses of the boiler.

Electric steam humidifiers are often extremely energy efficient and can have energy conversion rates of around 99% [38, 39, 40]. The calculated energy can be corrected to reflect this efficiency by dividing by this percentage.

Since electric steam humidifiers are often placed within the rooms itself, the steam transportation losses are considered to be negligible.

Next to these electricity costs, there are also the costs for the medium used, RO water. For the production of 1 kg steam, 1 litre of RO water is required. The costs for the RO water have to be added to obtain the operating costs of a decentralised electric steam boiler.

3.3.5 Humidification Load

The humidification load for a given universal air humidification system, as in figure 3.1, that is in equilibrium state, meaning that the humidity and temperature of the room are already at the desired values[2], can be determined using equation 3.21.

$$\text{load} = \text{target} - \text{recovered} - \text{inflow}, \tag{3.21}$$

---

[2] If that would not be the case, the load would either be larger or smaller until the desired levels are reached. At which the used equilibrium load is obtained again

where the *load* moisture content is the amount of moisture content that must be produced by the humidification system.

The *target* moisture content can be determined from the desired relative humidity and temperature, if a relative humidity level is maintained or the moisture content can be used directly, if a fixed moisture content level is maintained.

The *recovered* moisture content is the amount of moisture content recovered from the desiccant wheel.

The *inflow* moisture content is the amount of moisture content present in the outside air.

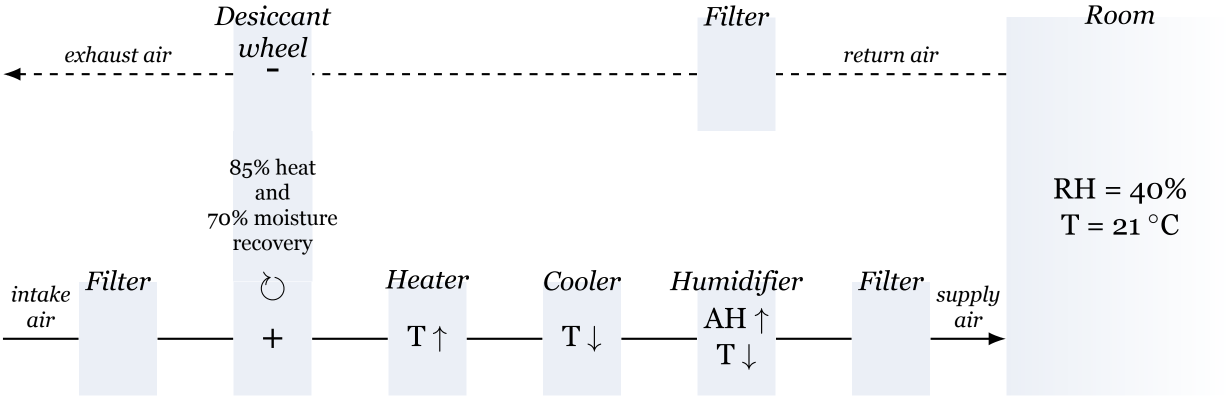

Figure 3.1: General AHU. The heater, cooler and humidifier can be turned on/off independently. During colder seasons, the heater is turned on and during warmer seasons, the cooler is turned on. The humidifier will only have an effect on temperature in the case that an adiabatic humidifier is used.

3.3.6 Energy for Heating

In adiabatic humidification, the air must be heated to offset the adiabatic cooling effect, the following calculation procedure can be used to give an estimation of the energy and costs for this process.

The amount of energy required to heat air from a certain temperature to a new temperature can be calculated using equation 3.15. The temperature to which the air will be heated will be denoted as T_{max}, to humidify 6 g/kg would result in T_{max} being around 15 °C higher than room temperature. After the adiabatic humidification has taken place, the air will have been cooled to the desired temperature, T_{des}, 21 °C for the UMCG. This results in a temperature difference of $\Delta T = T_{\text{max}} - T_{\text{des}}$.

The exact amount of energy that must be present in the air such that the setpoint temperature of the room is obtained after the adiabatic cooling effect is exactly equal to the amount of energy, in the form of heat, that is subtracted from the air to transfer the water to its gas state. This is given by change in enthalpy of water at that temperature but also by the latent heat of evaporation at a the temperature of the water. When this energy has been calculated or determined, equation 3.15 can be used to calculate the desired ΔT by using that Q equals the total amount of energy required for the evaporation of water.

3.3.7 Moisture Flow Model

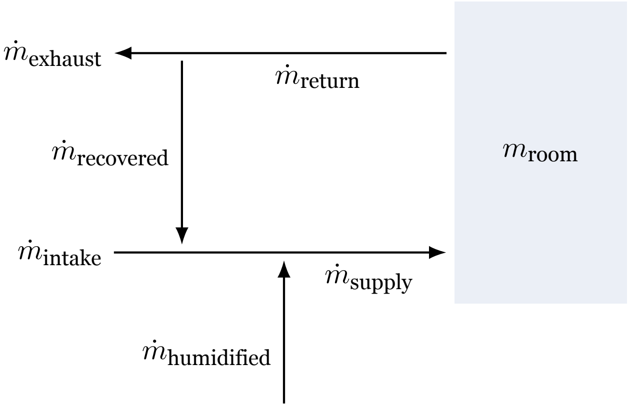

Figure 3.2: Description of mass flow and mass accumulation in the system. m_{room} denotes the total moisture mass present in the room in kilograms (kg). $\dot{m}_{\text{intake}}$, $\dot{m}_{\text{supply}}$, $\dot{m}_{\text{return}}$ and $\dot{m}_{\text{exhaust}}$ represent the total moisture mass in kilograms per unit of time present in an air flow, e.g. $\dot{m}_{\text{intake}}$ is the amount of moisture mass present in the intake air whereas $\dot{m}_{\text{recovered}}$ and $\dot{m}_{\text{humidified}}$ represent the total moisture mass in kilograms per unit of time present where the flow consists only of water vapour.

In figure 3.2, a general mass conservation system is illustrated. This system will be used to model the mass of water vapour in this system. $\dot{m}_{\text{intake}}$ is the total moisture mass present in the intake air per unit of time, $\dot{m}_{\text{humidified}}$ is the total moisture mass provided by the humidifier per unit of time, $\dot{m}_{\text{supply}}$ is the total moisture mass that is supplied to the room by the AHU per unit of time, m_{room} is the total moisture mass present in the room, $\dot{m}_{\text{return}}$ is the total moisture mass returned from the room per unit of time, $\dot{m}_{\text{recovered}}$ is the total moisture recovered by the desiccant wheel per unit of time and $\dot{m}_{\text{exhaust}}$ is the total moisture mass present in the exhaust air that is released back into the outside air per unit of time.

Note that any production and losses of moisture in the system are neglected.

Since an adiabatic system is considered, it could be argued that the system is a two variable system, with temperature and moisture content as inputs. That is, however, not the case. While it is true that the air has to be heated to a higher temperature to offset the adiabatic cooling effect. There has to be made a distinction between the heating required to reach the room setpoint temperature and the additional amount of heating required to offset the adiabatic cooling effect. The first part, heating to reach room temperature, occurs in both adiabatic and steam humidification and is actually not part of the humidification system but of the overall process of an AHU. Therefore, it is not of relevance for an indication of humidification costs. The latter, the additional amount to offset adiabatic cooling effect, is the only heating that should be taken into account. Since it can be assumed that the air before the humidifier has already been heated to room temperature, the energy required for the adiabatic cooling effect can be calculated and is not dependent on intake air temperature. Thus, the system becomes a single variable system that only depends on the amount of moisture in the intake/outside air.

From the mass flow analysis of figure 3.2, it follows that

$$\frac{dm_{\text{room}}}{dt} = \dot{m}_{\text{supply}} - \dot{m}_{\text{return}} \tag{3.22}$$

Variables

To calculate the total moisture mass and total moisture mass per hour for all the variables as given in the model, several paramaters have to be known.

These are,

- Volume of the room, V_{room} in m^3.
- Target temperature of the room, T_{room} in °C.
- The moisture content of the room, g_{room} in g/kg$_{\text{da}}$.
- The volumetric flow rate of the intake duct, $\dot{V}_{\text{duct,in}}$ in m^3/h.
- The absolute humidity of the intake/outside air, ρ_{intake} in g/m^3.
- The volumetric flow rate of the return duct, $\dot{V}_{\text{duct,out}}$ in m^3/h.
- The recovery rate of moisture of the desiccant wheel, $\%_{\text{recovery}}$, estimated to be around 70%.

Where $m_{\text{room}} = V_{\text{room}} \cdot \rho_{\text{room}}$, where ρ_{room} is the absolute humidity at room temperature.

Note that the amount of moisture can be given in three ways, as relative humidity, absolute humidity or moisture content. When given as relative humidity or moisture content, the temperature of the room and/or outside air must be known to convert it to absolute humidity, as the flow rate of the ducts is given in terms of volume.

To calculate the total moisture mass of intake air, m_{intake}, the mass of water vapour per cubic meter of air has to be obtained. This can be done by first converting the moisture content (g/kg$_{\text{da}}$) to the specific humidity using equation 3.13, which gives the amount of water vapour per mass of air (g/kg). Next, this can be converted by dividing by the specific volume, which can be calculated using equation 3.12, which will yield the absolute humidity (g/m^3). Lastly, this absolute humidity has to be multiplied with the volumetric flow rate $\dot{V}_{\text{duct,in}}$ to obtain the total moisture mass per unit of time.

The following formulas provided the values as required for the system in figure 3.2:

$$
\begin{aligned}
\dot{m}_{\text{intake}} &= \dot{V}_{\text{duct,in}} \cdot \rho_{\text{intake}} && (3.23)\\
\dot{m}_{\text{recovered}} &= m_{\text{return}} \cdot \%_{\text{recovery}} && (3.24)\\
\dot{m}_{\text{return}} &= \dot{V}_{\text{duct,out}} \cdot \rho_{\text{room}} && (3.25)\\
\dot{m}_{\text{exhaust}} &= \dot{m}_{\text{return}} - \dot{m}_{\text{recovered}} && (3.26)\\
& && (3.27)
\end{aligned}
$$

Equilibrium model

If it is assumed that the system is in equilibrium state, i.e. $\frac{dm_{\text{room}}}{dt} = 0$, it follows that

$$\dot{m}_{\text{supply}} = \dot{m}_{\text{return}}$$

Since m_{supply} is defined as,

$$\dot{m}_{\text{supply}} = \dot{m}_{\text{intake}} + \dot{m}_{\text{recovered}} + \dot{m}_{\text{humidified}},$$

it follows that,

$$
\begin{aligned}
&\dot{m}_{\text{intake}} + \dot{m}_{\text{recovered}} + \dot{m}_{\text{humidified}} = \dot{m}_{\text{return}}\\
\implies &\dot{m}_{\text{humidified}} = \dot{m}_{\text{return}} - \dot{m}_{\text{intake}} - \dot{m}_{\text{recovered}}\\
\implies &\dot{m}_{\text{humidified}} = (1 - \%_{\text{recovered}})\dot{m}_{\text{return}} - \dot{m}_{\text{intake}} \qquad (3.28)
\end{aligned}
$$

Next, the air humidification systems at the UMCG are only active when there is in fact a humidification load, i.e.

$$\dot{m}_{\text{intake}} + \dot{m}_{\text{recovered}} < \dot{m}_{\text{supply}},$$

which, given a certain target value for m_{supply}, implies there is an upper limit to the intake moisture mass

$$\dot{m}_{\text{intake}} < \dot{m}_{\text{supply}} - \dot{m}_{\text{recovered}}$$

Only when the value of $\dot{m}_{\text{intake}}$ is below this upper limit is there a need to humidify.

Dynamic cost model

The previous model assumed equilibrium conditions such that an initial operating cost comparison between adiabatic and steam humidification could be made. If it, however, is of interest to model the costs over time to provide better estimates of actual costs and gain insights into peak electricity consumption, a dynamic model can be created taking into account within room generation and losses, such as evaporation, condensation, open doors/windows, the following first order differential equation could be used.

$$\begin{aligned}
\frac{dm_{\text{room}}}{dt} &= \dot{m}_{\text{supply}} - \dot{m}_{\text{return}} + \Delta\dot{m}_{\text{system}} \\
&= \dot{m}_{\text{intake}} + \dot{m}_{\text{recovered}} + \dot{m}_{\text{humidified}} - \dot{m}_{\text{return}} + \Delta\dot{m}_{\text{system}} \\
&= \dot{m}_{\text{intake}} + \dot{m}_{\text{recovered}} + \dot{m}_{\text{humidified}} - \dot{m}_{\text{return}} + \Delta\dot{m}_{\text{system}} \\
&= \dot{m}_{\text{intake}} + (\%_{\text{recovered}} - 1)\dot{m}_{\text{return}} + \dot{m}_{\text{humidified}} + \Delta\dot{m}_{\text{system}} \qquad (3.29)
\end{aligned}$$

Results

When using the values of table 3.7 and using the equilibrium model, this yields a humidification load 10.890 kg/h. Which is equivalent to, 2.28 g/m^3/h or 1.89 g/kg$_{\text{da}}$/h.

For these calculations, the density of air has been considered to be constant throughout the system, at 1.204 kg/m^3, which is the density of air at 20°C [41], and the assumption has been made that the room has constant humidity throughout the entire room and that therefore the amount moisture and temperature of the air in the return duct are equal to that of the room.

Table 3.7: Determined parameter values of the pilot room in the UMCG

Variable	Value	Unit
V_{room}	1592	m^3
T_{room}	21	°C
φ_{room}	40	%
$V_{\text{duct,in}}$	4778	m^3/h
g_{intake}	0	g/kd$_{\text{da}}$
$\dot{V}_{\text{duct,out}}$	4953	m^3/h
$\%_{\text{recovery}}$	70	%

3.3.8 Cost Calculation Model

Now that the humidification load has been determined, the relevant costs can be calculated for the two alternative humidification methods, adiabatic humidification and electric steam humidification. For comparison, the resulting costs for the gas steam humidification system have also been calculated.

From empirical data of the EZT, the percentage of RO water effectively used in adiabatic humidification, using the EvaPack, has been taken as 70%. The estimated price of RO water, as calculated before, has been taken as € 6.27/m^3. The estimated averaged price of electricity has been taken as € 0.15490/kWh. The estimated steam loss during transportation for the gas powered steam has been taken as 15%, in accordance with the UMCG. Next, the steam price, in € /kg, for the gas powered steam system has been taken as 0.14057. And lastly, the amount of operating hours is taken as 24/7 operation during the humidification season, oct-dec and jan-mar, thus a total of $6/12 \cdot 365 \cdot 24\text{h} = 4380$ operating hours.

In the next 3 sections, the costs calculations for all these three humidification systems will be elaborated upon.

A screenshot of the developed model can be found in appendix F and a link to the download of the model is provided in append G. This model includes the cost calculations that will be described in the following three section.

Costs Gas Powered Steam Humidification System

Given a humidification load x =10.89040 kg/h and a percentage lost during transportation, $\%_{\text{lost}}$. The humidification load is $x/(1 - \%_{\text{lost}})$. Since the costs of the gas produced steam system at the UMCG are known, € 0.14057/kg, this yields a cost of € 1.80/h.

Costs Electric Steam Humidification System

The costs for an ESHS can be divided into the costs for heating the water and the costs for RO water.

The costs for heating can be calculated using the fact that the amount of steam required equals the humidification load x. Next, it has been determined earlier that the amount of energy required to boil the water and generate steam is 0.7314 kWh/kg. Taking into account that 1% of the energy is lost during this heating and using the humidification load x, yields a total energy consumption of 8.05 kWh/h. Given an energy price of € 0.15490/kWh, the total costs required for heating are € 1.25/h.

The costs for RO water can be calculated when the assumption is made that there are no steam transportation loss. Then the demand for RO water equals the humidification load x. Given that the price of RO water is € 6.27/m³, a total price of € 0.07/h for RO water is obtained.

Adding the costs for heating the water and the costs for the RO water, yields a total cost of € 1.31/h.

Costs Adiabatic Humidification System

The costs of an AHS can be divided into costs for heating the water to offset the adiabatic cooling effect and the costs for RO water.

The amount of energy required to evaporate the air is given by the latent heat of evaporation of water vapour at 20°C, 2453.5 kJ/kg [37]. Given the humidity load per hour x, this gives a total of 26719.59 kJ/h. By using the law of conservation of energy, this is also the amount of energy that is subtracted from the air in terms of heat. Using the specific heat capacity of air, 1.006 kJ/kg [42], and the specific heat capacity of water vapour, 1.863 kJ/kg [43], the temperature change can be calculated using the equation 3.15, $\Delta T = \frac{Q_{\text{evap}}}{m_{\text{a}} \cdot c_{\text{a}} + m_{\text{s}} \cdot c_{\text{s}}}$, Which yields a temperature change of 4.51°C. Note that the effect of heating the water vapour accounts for only 1.2% of the energy required for heating the air. Since the required amount of energy is already known as 26719.59 kJ/h, which is equivalent to 7.42 kWh/h, this can be used to calculate the costs required for heating. Using the electricity price of € 0.15490/kWh this yields a cost of € 1.15/h.

The costs for RO water can be calculated using the found 70% effective water usage and the humidification load x, yields a requirement of 15.56 liters RO water per hour. With a price of € 6.27/m³, this gives a cost of € 0.10/h.

Adding the costs for heating the air and the costs for the RO water, yields a total cost of € 1.25/h.

Overview of Costs and Energy of Humidification Systems

An overview of the costs and partial costs per humidification system can be found in table 3.8. It should be noted that these costs are not indicative of actual observed costs as a non representative inflow of 0 g/kg inflow is used. The findings however are indicative of the relative difference between the costs of these systems.

Table 3.8: Overview of the partial and total costs of each humidification system as found.

System	Costs			
	Electricity (€ /h)	RO water (€ /h)	Total (€ /h)	Total (€)
GPSHS	-	-	1.80	7888.26
ESHS	1.25	0.07	1.31	5758.11
AHS	1.15	0.10	1.25	5462.96

In order to make these costs indicative of what could be expected in real operation, the assumption of a fixed total operating hours has to be relaxed and the humidity of the outside air has to be known per desired time interval. This will be expanded upon in the next section.

What has also been calculated in these models is the amount of energy required for the humidification. Taking into account that a GPSHS has an energy loss of 17%[3] and the transportation loss of 15% results in a total of 0.7314/0.83/(1-0.15) = 1.0368 kWh/kg. An ESHS has an efficiency of 99% and transportation losses of 0%, resulting in a total energy demand of 0.7314/0.99=0.7388 kWh/kg and an AHS has a total energy demand of 0.6815 kWh/kg. From this it can be seen that an ESHS results in energy savings of 28.7% and an AHS requires 30.8% less energy. With regards to the water consumption of the systems, it was found that a ESHS uses an estimated 15.0% less energy while the AHS uses an estimated 21.4% more water.

An overview of the relative differences with regards to energy and water usage and costs between ESHS and AHS in comparison to the current GPSHS are provided in table 3.8.

Table 3.9: Overview of energy, water and cost savings of ESHS and AHS in comparison to gas powered steam humidification.

	ESHS	AHS
Energy	28.7%	34.3%
Water	15.0%	-21.4%
Costs	27.0%	30.8%

Comparison with Weather Data 2022

Using the 2022 weather data of Airport Eelde [44], the weather station of the Royal Netherlands Meteorological Institute (KNMI) near the UMCG provides hourly measurements of weather parameters, the actual operating costs of the UMCG can be calculated. The preliminary calculations to convert the hourly weather data into the saturation pressure and moisture content have been provided by the UMCG. An estimation of the actual volumetric flow rate of the overall air humidification system is given by the UMCG as 472 m^3/s. The model developed in this report has been updated to reflect this new volumetric flow rate.

The UMCG also calculates the amount of kilograms humidified per kilogram of dry air for the entire year. For the developed model this can be done by multiplying the amount of humidification in $g/kg_{da}/h$ with the estimated amount of operating hours, 4380 hours and then dividing by 1000. For the hourly weather data this can be done by

---

[3] The value of 83% energy conversion for gas is used by the UMCG, which equals an energy loss of 17%.

summing all hourly humidification loads and then dividing by 1000. This yields a total humidification of 8.00 kg/kg_{da} and 2.12 kg/kg_{da}, respectively.

Since the weather data gives the measurements on an hourly basis it is also possible to incorporate the actual energy price at that hour given that the monthly price is known and that it can be determined whether its peak or off-peak price and to what extend the humidification systems are utilised at that moment, e.g. 50% or 100%.

The outcomes of the model with fixed operating hours have been multiplied with a factor of 2.21/8.00 to test if this correction yields accurate estimations when comparing this to the weather data results with average and actual electricity prices.

The outcomes of the model, the model with actual weather data with average electricity price and the model with actual weather data with actual electricity price can be found in table 3.10. The overview of the estimated resources used can be found in table 3.11.

It must be noted that these results were obtained with the assumption that the 70% recovery rate of the desiccant wheel is valid for the entire humidification of the UMCG. That is however not the case, not all AHUs are equipped with a desiccant wheel.

To estimate the percentage of air humidification that uses a desiccant wheel. The following calculations have carried out. The UMCG in 2019 determined the amount of natural gas used for the production of steam for humidification, that is 1074392 m^3 of gas. When using the weather data of 2019 and calculating the amount of steam required knowing that it takes 0.7314 kWh/kg to produce steam, the efficiency of the steam production is 83% as provided by the UMCG and the transportation losses of 15% yield a total energy requirement of 4407211.10 kWh. It is provided by the UMCG that 1 MWh equals 102 m^3 of gas. This yields a total gas consumption of 449535.53 m^3 in 2019 using desiccant wheels in each room. Thereby the percentange of humidification that contains a desiccant is given by $449535.53/1074392 = 41.8\%$.

The outcomes of the model, the model with actual weather data with average electricity price and the model with actual weather data with actual electricity price, all including the updated desiccant wheel percentage can be found in table 3.12 and the overview of the estimated resource used can be found in table 3.13.

Table 3.10: Overview of total costs of the developed model adjusted to reflect the actual humidification load with comparison to the a model which included the 2022 weather data and the average electricity price and a model based on the 2022 weather data that used the monthly electricity price and considered peak and off-peak hours. The percentage difference refers to the adjusted cost of the first model to that model.

	0 moisture inflow and fixed operating hours	adjusted by factor 2.12/8.00	Hourly with average electricity price	percentage difference with adjusted	Hourly with peak and off-peak electricity price	percentage difference with adjusted
GPSHS	€ 2,706,184.95	€ 718,454.32	€ 718,530.95	0.01%	-	-
ESHS	€ 1,975,403.56	€ 524,404.75	€ 524,455.55	0.01%	€ 542,706.96	3.37%
AHS	€ 1,874,150.63	€ 497,525.43	€ 497,593.94	0.01%	€ 514,430.76	3.29%

Table 3.11: Overview of resource utilisation for actual weather conditions of 2022.

	RO water m³		Electricity MWh		Gas m³
GPSHS	5116.6	+17.6%	-	-	459441.1
ESHS	4344.8	-	3209.9	+8.4%	-
AHS	6206.9	+42.9%	2961.1	-	-

Table 3.12: Overview of total costs of the developed model adjusted to reflect the actual humidification load, when taking into account that 41.8% of the total humidification incorporates a desiccant wheel, with comparison to the a model which included the 2022 weather data and the average electricity price and a model based on the 2022 weather data that used the monthly electricity price and considered peak and off-peak hours. The percentage difference refers to the adjusted cost of the first model to that model.

	0 moisture inflow and fixed operating hours	adjusted by factor 5.01/8.00	Hourly with average electricity price	percentage difference with adjusted	Hourly with peak and off-peak electricity price	percentage difference with adjusted
GPSHS	€2,706,184.95	€1,694,115.28	€1,694,295.99	0.01%	-	-
ESHS	€1,975,403.56	€1,236,546.41	€1,236,666.20	0.01%	€1,279,703.01	3.37%
AHS	€1,874,150.63	€1,173,164.96	€1,173,326.50	0.01%	€1,213,027.73	3.29%

Table 3.13: Overview of resource utilisation for actual weather conditions of 2022.

	RO water m^3		Electricity MWh		Gas m^3
GPSHS	12053.0	+17.6%	-	-	1083362.2
ESHS	10245.1	-	7568.9	+8.4%	-
AHS	14635.8	+42.9%	6982.3	-	-

3.4 Regulations

There are several guidelines provided for which humidity levels should be maintained within hospitals and specific areas [3, 45, 46] whereas [8] lists standards specifically for ORs.

As noted by the TNO, there are not many of these standards that apply to hospitals in the Netherlands. Also, the standards in [3, 46] do not list any standards or regulations specifically for hospitals in the Netherlands. [45] lists one requirement from the college construction and hospital facilities and can be found in table 3.14.

There is one regulation which has also been mentioned in section 2.1.1. That is article 4.87b in the Arbowet which requires a RAE in case any humidification method other than steam is used.

It was found in the interviews that there are two manuals aimed at preventing Legionella, these are the ISSO 55.1 and VDI 6022. While the VDI 6022 is only applicable to Germany, manufacters do use it to get a VDI 6022 certification which shows customers they have taken the prevention of Legionella growth into account while developing the system.

Table 3.14: Overview requirements from college construction and hospital facilities as listed in [45].

Function	RH (%)		T (°C)	
	min	max	min	max
Incubator rooms	-	-	20	28
High care	50	-	0	24
Intensive care	50	-	-	24
Central sterilisation department	50	75	-	-
Operating room	-	-	21 ± 3	-

Chapter 4

Discussion

The interviews with the other hospitals showed that there were little to no insights into the resource usage of their humidification systems. For individual AHUs there was no information available with regards to amount of energy and water consumption, nor was it available for the humidifiers within the AHUs.

Some hospitals indicated that the operational costs presented to them by suppliers were based on the systems at DZ. These are significantly lower as the costs for the additional heating to offset the adiabatic cooling effect are reduced due to the interconnection with the ATES system. These operational cost indications were therefore not representative for them.

Most hospitals did not have any measurements or indications available to the energy usage or water consumption of individual AHUs. Thereby there was no clear picture of the operating costs for potential ESHSs and AHSs. Historically, the air humidification within hospitals has been humidified via a centralised steam generators. The UMCG did have insights into the resources used by, and the costs associated to these steam generators. Because of this central steam generation which accounts for a significant amount of the total energy for humidification, it has always been of lower interest to measure the energy consumed by the humidifiers within the AHUs. When transitioning towards ESHSs and/or AHSs the energy that is used by the humidification process moves to the decentralised AHUs and humidifiers.

To provide an estimation of the operating costs to the UMCG, a model has been developed that provides an estimation of the operating costs of the current central GPSHS, a general decentralised ESHS and a general decentralised AHS. This model first determines the humidification load based on several input parameters, then calculates the resource required based on several assumptions and finally gives an estimation of the operating costs for each of the three humidification systems.

The results showed that the model did not yield accurate results when assuming 0 moisture inflow and 4380 operating hours. The model yielded a total yearly humidification requirement of 8.00 kg/kg$_{da}$ whereas the model that used actual weather data showed that only a total of 2.12 kg/kg$_{da}$ was humidified when all AHUs used a desiccant wheel and 5.01 kg/kg$_{da}$ was humidified when the estimated 41.8% of the rooms used a desiccant wheel.

It was then assessed whether the a correction for this deviation in total humidification load would result in a better approximation of operational costs. It was found that a correction yielded accurate results that differed only 0.01% for all of the three systems. It was also found that when incorporating the actual electricity prices with the weather data, the original model, after the correction for the humidification load, deviated only 3.27% and 3.29% for the ESHS and AHS, respectively. This shows that the method of calculating the average electricity price, using the humidification season months only, yields an accurate estimations of the costs observed for humidification.

It was found that after a correction for the humidification load, the model yielded accurate estimations and that the average yearly electricity price did not result in significant deviations from the actual electricity price. Therefore, it can be said that the simple model based on a fixed amount of operating hours, average electricity price and zero inflow moisture can be used to give accurate estimations when it is corrected for the error in humidification load. Especially with regards to a relative comparison in percentages, the results are representative regardless of correction for humidification load.

The model also provided an estimation of the total amount of gas consumed by the GPSHS. For the current GPSHS at the UMCG, where not every AHU is equipped with a desiccant wheel, it was found that a total of 1083362.2 m^3 of gas was required whereas when each AHU contained a desiccant wheel only 459441.1 m^3 of gas was required. This shows that using a desiccant wheel is a very effective way to reduce total gas consumption and will therefore also be one of the points of advice for the UMCG.

The UMCG had a total gas consumption of 7172180 m^3 in 2022. The developed model shows that the GPSHS accounted for 15.1% of the UMCGs gas consumption in 2022.

In addition to a reduction of the consumption of gas, it was also shown that using ESHSs and/or AHSs results in a reduction of operating costs.

The outcomes of this model showed that the results were not indicative when comparing these to the outcomes with actual weather data. The model yielded estimations of € 2,706,184.95, € 1,975,403.56 and € 1,874,150.63 for the GPSHS, ESHS and AHS, respectively. Whereas when incorporating the hourly weather data and the actual electricity prices yielded cost estimations of € 1,694,295.99, € 1,279,703.01 and € 1,213,027.73 for the GPSHS, ESHS and AHS, respectively. When correcting for the total humidification load, the model yielded operating cost estimations of € 1,694,115.28, € 1,236,546.41 and € 1,173,164.96 for the GPSHS, ESHS and AHS, respectively. It can be seen that these values are much closer to the estimations and it was shown that these values deviated only 3.27% and 3.29% for the GPSHS and AHS, respectively.

It was also shown that the total operating costs are also significantly reduced if desiccant wheel are used in all humidification systems. When desiccant wheels were incorporated in all humidification systems, the operational cost estimations were reduced to €718,530.95, €524,455.55 and €497,593.94 for the GPSHS, ESHS and AHS, respectively.

From these findings it was shown that, with respect to GPSHS, the estimated costs of an ESHS are 27.0% lower and for an AHS the costs 30.8% lower.

What also became clear from the interviews with the TNO and the MUMC and from the paper published by TNO [26] is that the arguments for which humidification is required do not all have a sound scientifically basis. The UMCG currently humidifies to a relative humidity of 40% and the research from the TNO proposed a lower limit of 30%. This shows that the UMCG could potentially reduce the humidity levels to somewhere between 30% and 40% to reduce gas.

As was established in the interviews, there is currently a movement towards reducing the overall amount of humidification, therefore it should not only be considered to switch to adiabatic/decentralised humidification, but also to assess for each room/department whether humidification is necessary. Research from TNO for the Erasmus MC will give insights into the microbiological properties of adiabatic systems in comparison to steam systems.

Chapter 5

Conclusion

5.1 Answering of Research Questions

To answer the main research question, **how can a new decentralised humidification system be selected that satisfies the requirements and demands of the UMCG?**, several sub-research questions were developed to to help in answering this main research question. In this chapter, first these sub-research questions will be answered whereafter the main research question will be answered.

What are the requirements and guidelines for air humidification systems within a health care facility setting, regulatory and customer specific?

The guidelines and regulations for humidification systems within hospitals can be divided into two categories. These are with respect to the microbiological safety of the system and with respect to the humidity levels or ranges that must be maintained within rooms.

With respect to the microbiological safety, one guideline and one regulation that applied to the UMCG were found during this study.

The regulation that was found, the Arbowet article 4.87b, states that for any humidification system other than steam, the measures at preventing Legionalla are considered to be effective if the number of CFUs is below 100 per litre. In addition, the Arbowet also requires a RAE if any humidification method other than steam humidification is used.

The guideline that was found, the ISSO 55.1, is a manual for hospitals on how to construct their humidification systems and water pipes for Legionella prevention. Another guideline that is often used by manufacturers is the VDI 6022. This is a guideline in Germany also aimed at the prevention of Legionella. It was found that a VDI 6022 certified system has been developed with the prevention of Legionella formation in mind.

The main drawbacks of the ISSO 55.1 and VDI 6022 guidelines are that they are of a more qualitative nature and the humidification systems that have received VDI 6022 certification are designed with the prevention of Legionella growth in mind but do have the property that if Legionella is already in the medium, it can potentially enter the air whereas in steam humidification the Legionella in the medium are killed due to the water temperature.

With respect to the humidity levels, only one guideline was found during this study. That is the one provided by the college construction and hospital facilities. This guideline gives several parameter values for air humidity and temperature for five room types.

What are the costs associated with the different types of humidification systems, i.e. GPSHSs, ESHSs and AHSs?

It was established that the current GPSHS had estimated operational costs of € 1,694,115.28 in 2022. By transitioning to ESHSs and AHSs it was shown that these costs would reduce to € 1,236,546.41 and € 1,173,164.96, respectively. Next to that, it was concluded that by installing desiccant wheels in each AHU these costs could be further reduced to € 524,404.75 and € 497,525.43 for ESHSs and AHSs, respectively.

How much resources are used by the different humidification systems with regards to gas, electricity and water?

From the results obtained by the develop model it was established that there were significant differences in the resource used by the three humidification systems. It was estimated that the ESHS and AHS would result in energy savings of 28.7% and 34.3% with respect to the current GPSHS, respectively. It was also found that the ESHS would save an estimated 15.0% in RO water while the AHS will result in additional 21.4% of RO water used when compared to the current GPSHS. That is, when comparing the models that have an equal percentage of desiccant wheels. When comparing the data of 2022 with 41.8% desiccant wheels to the ESHS and AHS model with desiccant wheels. The UMCG would reduce their RO water consumption from 12053.0 m^3 to 4344.8 m^3 when using ESHSs and to 6206 m^3 when using AHSs.

It was also shown that the current GPSHS used 1083362.2 m^3 of gas. By switching to ESHSs and AHSs the UMCG would reduce their total gas consumption by 15.1%.

What are the available options to evaluate the performance and resource usage of air humidification systems?

During this study it was found that the measurements for performance of air humidification systems within hospitals is very limited. Most hospitals measured the humidity of the rooms but had very little insights into the resources consumed by their humidification systems. It was argued this could possibly be attributed to the historical use of centralised steam production. Since the steam was provided to the actual humidification systems, the humidifiers had a relatively low impact on energy consumption.

However, when transitioning towards decentralised humidification systems, these cost will also move these decentralised systems.

In the transition of moving towards decentralised methods of air humidification it could for, performance optimisation, cost reduction/insights and increased sustainability, be very insightful to start measuring the resources used by the individual AHUs and the air humidification systems.

A list of several potential performance indicators is proposed

- The amount of RO water effectively used in the humidification process, by measuring the drained water.
- The amount of energy required for the humidification process, by measuring the electricity and, in case adiabatic humidification is used, the amount of energy required for heating
- The amount of energy required by the humidifier

To answer the main research question, **how can a new decentralised humidification system be selected that satisfies the requirements and demands of the UMCG?**.

It was found there were mainly two AHSs that are used within hospitals. These are the EvaPack and the Condair DL. It was found that the selection of an air humidification system is dependent on many factors and also depends on the specific goals and intentions of the humidification system. Therefore, this study has aimed to give insights into the operational differences between the three humidification systems. It is important to note that these estimations exclude the investment and maintenance costs.

To select a humidification system the UMCG should first assess which ESHS and AHS they are considering and then ask for quotes from suppliers with more details of the size of the desired humidification system. In combination with the model from this report, the UMCG can then select a system that satisfies their requirements and that also has the lowest TCO.

5.2 Final Recommendations

Taking into account that there is also discussion on whether humidification is required and to what extend humidification is required, i.e. which humidity levels are desired, there are a certain number of steps that can be undertaken to reduce the costs required for humidification

1. Utilise desiccant wheels where possible.

2. Reduce humidification areas to where strictly required/desirable.
3. Reduce level to which is humidified.
4. Use adiabatic humidification systems where possible, if, and where, allowed by infection prevention.
5. Use decentralised electric steam humidifiers.

5.3 Future Research

5.3.1 Validation of Model

The UMCG currently does not measure the electricity or water consumed on the level of an individual air humidifier or even on the level of an AHU. In order to validate the operational cost estimations, several measurements must be made regarding the energy required for heating, the amount of RO water consumed and lost during the humidifying process. At this moment all the calculations have a theoretical basis and it is unclear whether significant deviations will be observed under actual operation conditions.

5.3.2 Adiabatic and Microbiological Implications

The main reason for many hospitals to not switch to adiabatic humidification is with regards to the hygienic implications. From the interviews with hospitals and researchers it became clear that much remains uncertain. The TNO is currently doing research to investigate the microbiological differences between steam and adiabatic humidifiers to compare the adiabatic systems to a steam based system that is considered to be safe and the outcomes of this research can be very helpful.

Since the UMCG is also running their own pilot with an adiabatic humidifier, it can be insightful to perform periodic testing on microbiological organisms to get a better image of the safety of adiabatic humidification with regards to microbiological safety.

5.3.3 Deviations in Energy Consumption from Controller

The model created to assess the energy usage, and the costs of, an adiabatic and electric steam humidifier it was assumed that the system is in equilibrium, i.e. amount of moisture in the room remains unchanged. Whilst it does give a good indication of overall costs, it gives no insights into fluctuations of the energy consumption if the humidification load increases temporarily. Therefore, it is important to research and assess the peak electricity and water demands such that the whole system is build to allow for these temporarily peaks in operation.

5.3.4 Water Efficiency of Adiabatic Humidification Systems

The EvaPack from HygroTemp advertises a 100% conversion of water. This efficiency is however not seen in practice. In fact, the EZT had a RO water loss of approximately

30%. The UMCG also experiences some water loss, of which the extend is currently unknown. It is therefore advised to research how the controller of the EvaPack can be adjusted to increase the efficiency of the water usage to reduce the resource used by this system and to reduce operational costs.

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Appendix A ISO 14611-1

Table A.1: ISO Classification 14644-1 [47]

ISO Class number (N)	Maximum allowable concentrations (particles/m^3) for particles equal to and greater than the considered sizes[a]					
	0.1 μm	0.2 μm	0.3 μm.	0.5 μm	1 μm	5 μm
1	10[b]	[d]	[d]	[d]	[d]	[e]
2	100	24[b]	10[b]	[d]	[d]	[e]
3	1 000	237	102	35[b]	[d]	[e]
4	10 000	2 370	1 020	352	83[b]	[e]
5	100 000	23 700	10 200	3 520	832	[d, e, f]
6	1 000 000	237 000	102 000	35 200	8 320	293
7	[c]	[c]	[c]	352 000	83 200	2 930
8	[c]	[c]	[c]	3 520 000	832 000	29 300
9[g]	[c]	[c]	[c]	35 200 000	8 320 000	293 000

[a] All concentrations in the table are cumulative, e.g. for ISO Class 5, the 10 200 particles shown at 0.3 μm include all particles equal to and greater than this size.

[b] These concentrations will lead to alrge air sample volumes for classification. Sequential sampling procedure may be applied.

[c] Concentration limits are not applicable in this region of the table due to very high particle concentration

[d] Sampling and statistical limits are not applicable in this region of the table due to very high particle concentration

[e] Sample collection limitations for both particles in low concentrations and sizes greater than 1 μm make classification at this particle size inappropriate, due to potential particle losses in the sampling system.

[f] In order to specify this particle size in association with ISO Class 5, the macroparticle descriptor M may be adapted and used in conjunction with at least one other particle size.

[g] This class is only applicable for the in-operation state.

Appendix B Sterling Chart

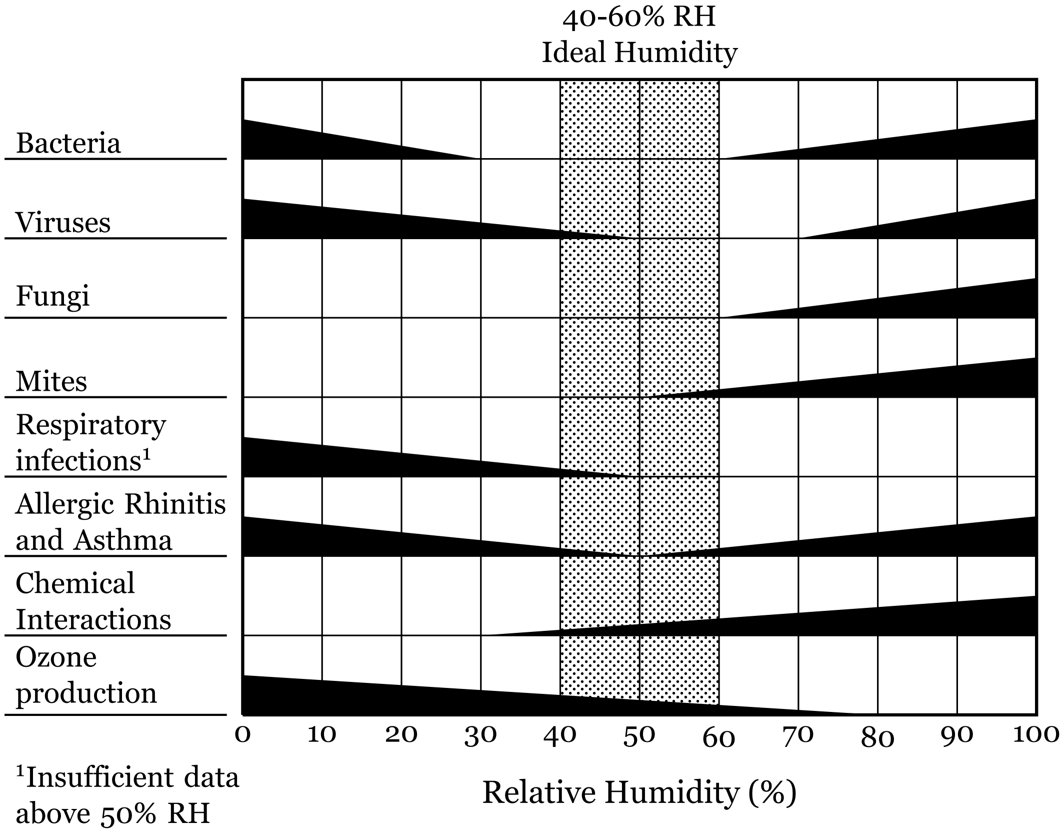


Figure B.1: Sterling chart. A decrease in bar width indicates decrease in effect

Appendix C Effect of Air Temperature on Humidity

Relative air humidity can be calculated as

$$RH = \frac{\text{vapour pressure}}{\text{saturated vapour pressure}} = \frac{P_w}{P_{ws}} \tag{1}$$

$$P_{ws} = 0.61121e^{\left(\left(18.678-\frac{T}{234.5}\right)\left(\frac{T}{257.14+T}\right)\right)} \tag{2}$$

Since the calculations of the saturated vapour pressure are dependent on non-constant variables, several approximation methods have been developed. For this, the Arden Buck approximation is used, which is specifically developed for the 0°C to 50 °C range and is one of the most accurate approximation techniques. Using the Arden Buck approximation to calculate the saturated vapour pressure and the resulting decrease in humidity yields table C.1. In this table, it can be seen that at a temperature of 18 degrees Celsius, a one degree increase results in a decrease in relative air humidity of 6.074% while a one degree decrease results in an increase in air humidity of 5.767%. These values have been calculated over the entire range of 0°C-50°C.

Since the operating range for hospitals is approximately between 18°C and 25°C. It can be observed that within this range an increase of 1°C results in a decrease of about 6.1 to 5.7 percent in air humidity, whereas a decrease of 1°C results in an increased air humidity of about 5.4 to 5.8 percent.

Table C.1: Effect of a 1°C air temperature change on relative humidity. Only the relevant range within hospitals is displayed here.

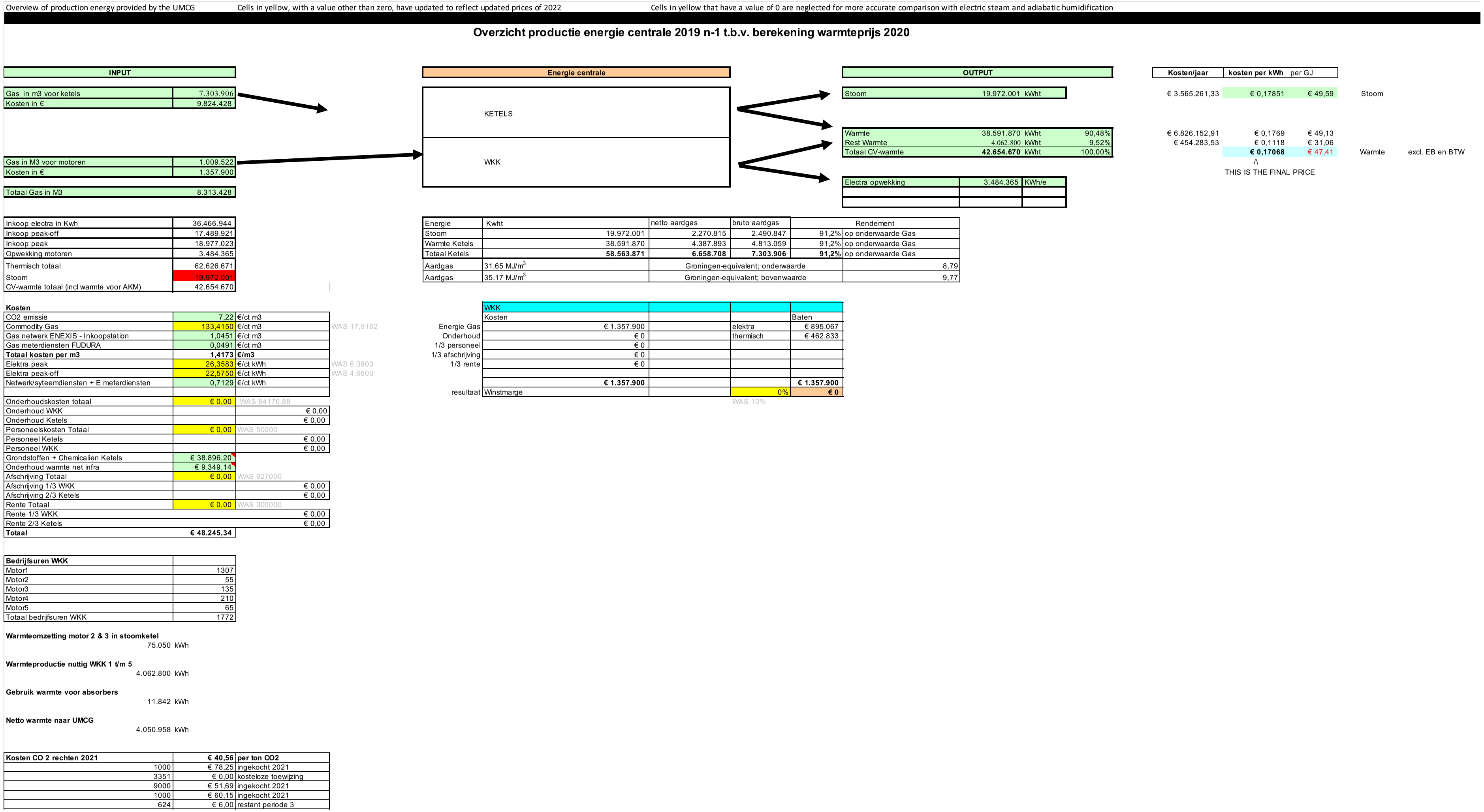
Temperature	*1°C increase* **Decrease in RH**	*1°C decrease* **Increase in RH**
°C	%	%
18	6.074	5.767
19	6.028	5.726
20	5.984	5.686
21	5.939	5.646
22	5.895	5.606
23	5.852	5.567
24	5.808	5.528
25	5.766	5.490

Appendix D Gas and Electricity Prices UMCG 2022

Table D.1: Gas and electricity prices of the UMCG for the year 2022. The prices are gives in euros per MWh, excluding VAT and taxes.

	Gas	**Electricity**	
	Peak	Off-Peak	24h
Jan	117	230	165
Feb	85	190	153
Mar	81	272	251
Apr	132	210	186
May	102	181	178
Jun	94	217	204
Jul	107	310	302
Aug	171	460	436
Sep	236	375	319
Oct	204	177	141
Nov	136	219	153
Dec	168	322	221

Appendix E Overview UMCG Power Plant for Cost Calculations per kWh for Steam.



Overview of production energy provided by the UMCG

Cells in yellow, with a value other than zero, have updated to reflect updated prices of 2022

Cells in yellow that have a value of 0 are neglected for more accurate comparison with electric steam and adiabatic humidification

Overzicht productie energie centrale 2019 n-1 t.b.v. berekening warmteprijs 2020

INPUT	
Gas in m3 voor ketels	7.303.906
Kosten in €	9.824.428
Gas in M3 voor motoren	1.009.522
Kosten in €	1.357.900
Totaal Gas in M3	8.313.428

OUTPUT			
Stoom	19.972.001	kWht	
Warmte	38.591.870	kWht	90,48%
Rest Warmte	4.062.800	kWht	9,52%
Totaal CV-warmte	**42.654.670**	kWht	100,00%
Electra opwekking	3.484.365	KWh/e	

Kosten/jaar	kosten per kWh	per GJ		
€ 3.565.261,33	€ 0,17851	€ 49,59	Stoom	
€ 6.826.152,91	€ 0,1769	€ 49,13		
€ 454.283,53	€ 0,1118	€ 31,06		
	€ 0,17068	€ 47,41	Warmte	excl. EB en BTW

/\
THIS IS THE FINAL PRICE

Inkoop electra in Kwh	36.466.944
Inkoop peak-off	17.489.921
Inkoop peak	18.977.023
Opwekking motoren	3.484.365
Thermisch totaal	62.626.671
Stoom	19.972.001
CV-warmte totaal (incl warmte voor AKM)	42.654.670

Energie	Kwht	netto aardgas	bruto aardgas	Rendement	
Stoom	19.972.001	2.270.815	2.490.847	91,2%	op onderwaarde Gas
Warmte Ketels	38.591.870	4.387.893	4.813.059	91,2%	op onderwaarde Gas
Totaal Ketels	**58.563.871**	**6.658.708**	**7.303.906**	**91,2%**	op onderwaarde Gas
Aardgas	31.65 MJ/m^3	Groningen-equivalent; onderwaarde			8,79
Aardgas	35.17 MJ/m^3	Groningen-equivalent; bovenwaarde			9,77

Kosten

CO2 emissie	7,22	€/ct m3	
Commodity Gas	133,4150	€/ct m3	WAS 17,9162
Gas netwerk ENEXIS - Inkoopstation	1,0451	€/ct m3	
Gas meterdiensten FUDURA	0,0491	€/ct m3	
Totaal kosten per m3	**1,4173**	**€/m3**	
Elektra peak	26,3583	€/ct kWh	WAS 6.0900
Elektra peak-off	22,5750	€/ct kWh	WAS 4.6600
Netwerk/syteemdiensten + E meterdiensten	0,7129	€/ct kWh	
Onderhoudskosten totaal	€ 0,00	WAS 84170,88	
Onderhoud WKK		€ 0,00	
Onderhoud Ketels		€ 0,00	
Personeelskosten Totaal	€ 0,00	WAS 50000	
Personeel Ketels		€ 0,00	
Personeel WKK		€ 0,00	
Grondstoffen + Chemicalien Ketels	€ 38.896,20		
Onderhoud warmte net infra	€ 9.349,14		
Afschrijving Totaal	€ 0,00	WAS 927000	
Afschrijving 1/3 WKK		€ 0,00	
Afschrijving 2/3 Ketels		€ 0,00	
Rente Totaal	€ 0,00	WAS 300000	
Rente 1/3 WKK		€ 0,00	
Rente 2/3 Ketels		€ 0,00	
Totaal	**€ 48.245,34**		

	WKK			
	Kosten			Baten
Energie Gas	€ 1.357.900		elektra	€ 895.067
Onderhoud	€ 0		thermisch	€ 462.833
1/3 personeel	€ 0			
1/3 afschrijving	€ 0			
1/3 rente	€ 0			
	€ 1.357.900			**€ 1.357.900**
resultaat	Winstmarge		0%	**€ 0**
			WAS 10%	

Bedrijfsuren WKK	
Motor1	1307
Motor2	55
Motor3	135
Motor4	210
Motor5	65
Totaal bedrijfsuren WKK	1772

Warmteomzetting motor 2 & 3 in stoomketel
75.050 kWh

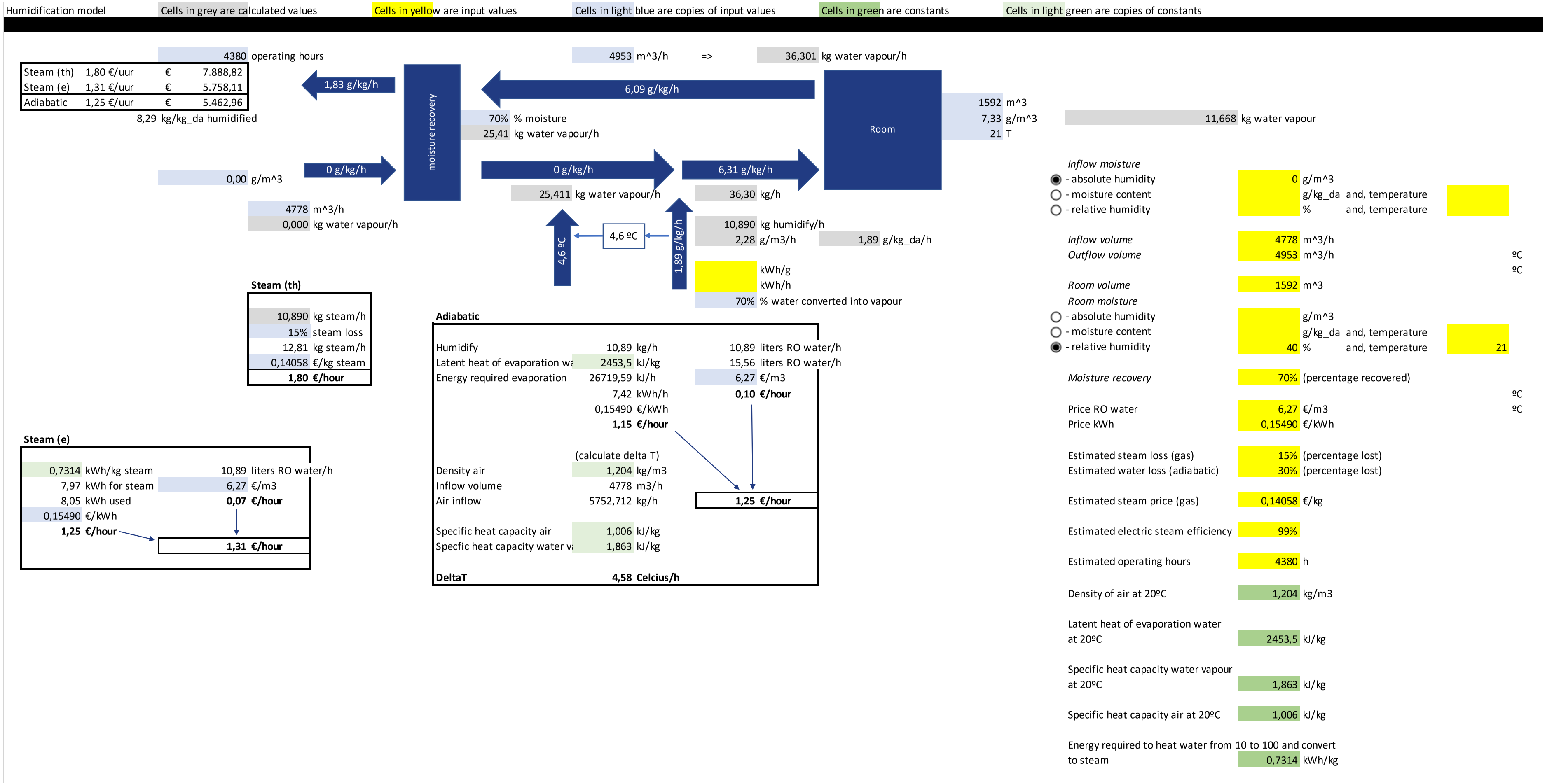
Warmteproductie nuttig WKK 1 t/m 5
4.062.800 kWh

Gebruik warmte voor absorbers
11.842 kWh

Netto warmte naar UMCG
4.050.958 kWh

Kosten CO 2 rechten 2021	**€ 40,56**	**per ton CO2**
1000	€ 78,25	ingekocht 2021
3351	€ 0,00	kosteloze toewijzing
9000	€ 51,69	ingekocht 2021
1000	€ 60,15	ingekocht 2021
624	€ 6,00	restant periode 3

Appendix F Developed Humidification and Cost Model



Humidification model | Cells in grey are calculated values | Cells in yellow are input values | Cells in light blue are copies of input values | Cells in green are constants | Cells in light green are copies of constants

4380 operating hours

Steam (th)	1,80 €/uur	€	7.888,82
Steam (e)	1,31 €/uur	€	5.758,11
Adiabatic	1,25 €/uur	€	5.462,96

8,29 kg/kg_da humidified

0,00 g/m^3

4778 m^3/h
0,000 kg water vapour/h

4953 m^3/h => 36,301 kg water vapour/h

70% % moisture
25,41 kg water vapour/h

25,411 kg water vapour/h

36,30 kg/h

10,890 kg humidify/h
2,28 g/m3/h

1,89 g/kg_da/h

kWh/g
kWh/h
70% % water converted into vapour

1592 m^3
7,33 g/m^3
21 T

11,668 kg water vapour

Steam (th)

10,890 kg steam/h
15% steam loss
12,81 kg steam/h
0,14058 €/kg steam
1,80 €/hour

Steam (e)

0,7314 kWh/kg steam
7,97 kWh for steam
8,05 kWh used
0,15490 €/kWh
1,25 €/hour

10,89 liters RO water/h
6,27 €/m3
0,07 €/hour

1,31 €/hour

Adiabatic

Humidify	10,89	kg/h	10,89	liters RO water/h
Latent heat of evaporation wa	2453,5	kJ/kg	15,56	liters RO water/h
Energy required evaporation	26719,59	kJ/h	6,27	€/m3
	7,42	kWh/h	**0,10**	**€/hour**
	0,15490	€/kWh		
	1,15	**€/hour**		

(calculate delta T)

Density air	1,204	kg/m3
Inflow volume	4778	m3/h
Air inflow	5752,712	kg/h
Specific heat capacity air	1,006	kJ/kg
Specfic heat capacity water va	1,863	kJ/kg
DeltaT	**4,58**	**Celcius/h**

1,25 €/hour

Inflow moisture
● - absolute humidity 0 g/m^3
○ - moisture content g/kg_da and, temperature
○ - relative humidity % and, temperature

Inflow volume 4778 m^3/h
Outflow volume 4953 m^3/h ºC
ºC

Room volume 1592 m^3
Room moisture
○ - absolute humidity g/m^3
○ - moisture content g/kg_da and, temperature
● - relative humidity 40 % and, temperature 21

Moisture recovery 70% (percentage recovered)
ºC
ºC

Price RO water	6,27	€/m3
Price kWh	0,15490	€/kWh
Estimated steam loss (gas)	15%	(percentage lost)
Estimated water loss (adiabatic)	30%	(percentage lost)
Estimated steam price (gas)	0,14058	€/kg
Estimated electric steam efficiency	99%	
Estimated operating hours	4380	h
Density of air at 20ºC	1,204	kg/m3
Latent heat of evaporation water at 20ºC	2453,5	kJ/kg
Specific heat capacity water vapour at 20ºC	1,863	kJ/kg
Specific heat capacity air at 20ºC	1,006	kJ/kg
Energy required to heat water from 10 to 100 and convert to steam	0,7314	kWh/kg

Appendix G Supporting Documents

The excel model and the model with the KNMI weather data of 2022 can be found at
`http://tiny.cc/m1l3vz`

or alternatively at
`https://doi.org/10.5281/zenodo.7554864`