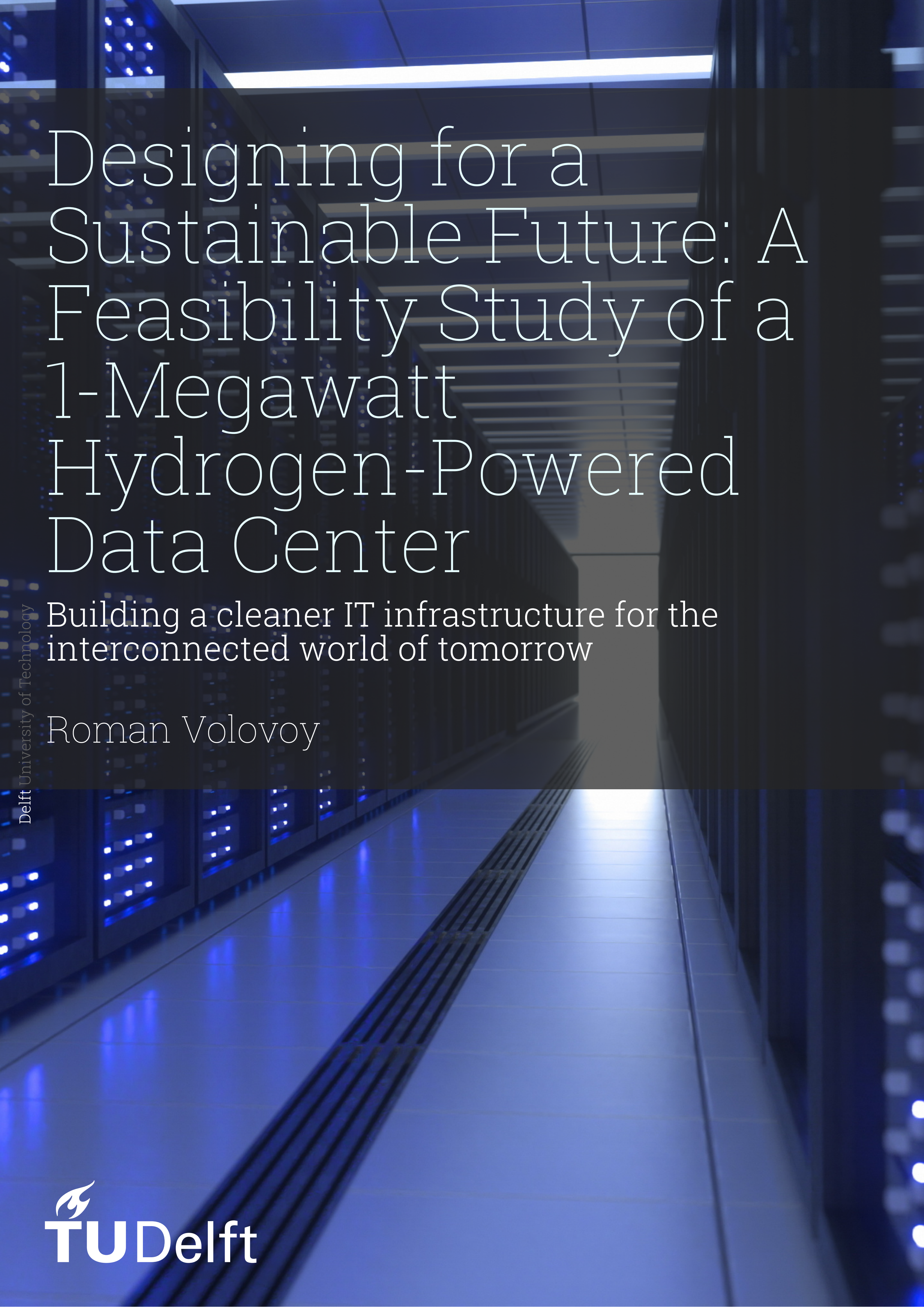


Designing for a Sustainable Future: A Feasibility Study of a 1-Megawatt Hydrogen-Powered Data Center

Building a cleaner IT infrastructure for the interconnected world of tomorrow

Roman Volovoy

Delft University of Technology

TUDelft

Designing for a Sustainable Future: A Feasibility Study of a 1-Megawatt Hydrogen-Powered Data Center

Building a cleaner IT infrastructure for the interconnected world of tomorrow

by

Roman Volovoy

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Monday August 26, 2024 at 3 PM.

Student number:	5219760	
Project duration:	December 7th, 2023 – August 26, 2024	
Thesis committee:	Dr. Zian Qin,	TU Delft, Thesis Advisor, DCE&S
	Dr. Hani Vahedi,	TU Delft, Supervisor, DCE&S
	Dr. Hesan Ziar,	TU Delft, Jury, PVMD

An electronic version of this thesis is available at https://repository.tudelft.nl/.

TU Delft

Preface

This thesis project has been equally challenging and fulfilling. For the last eight months, I have researched, analyzed, and evaluated the complex data center industry.

While writing this report, I assumed the reader had a basic knowledge of computers and information technology. However, readers need not be familiar with modern data center trends, as the comprehensive review is available in Chapter 2. Readers familiar with data center technologies can skip ahead to Chapter 4 for the complete design overview of the proposed hydrogen data center.

I would like to thank my daily supervisor, Dr. Hani Vahedi, for his guidance and mentorship in writing a technical literature review thesis. Dr. Vahedi suggested this topic to me, and at first I did not understand its complexity. However, as I researched more, I went down a deep rabbit hole of resiliency and reliability required in data center deployments. Towards the end of the research, I became increasingly optimistic about the potential of using hydrogen as an energy carrier in data centers. I hope this study will contribute to the push for sustainability in our ever-growing digital lives.

I would also like to acknowledge Dr. Rene Pecnik for confirming my assumptions regarding the thermal system proposed in this research. I am also grateful to Victor Barrera Consuegra for his constructive criticism and proofreading assistance. Finally, I would like to express my gratitude to TU Delft University for providing me with the opportunity to conduct this research and for enabling me to access a wide range of academic resources.

Roman Volovoy
Delft, August 2024

Abstract

This report proposes a design of a 1-megawatt data center that utilizes hydrogen as the primary fuel for power and cooling. Currently, data centers rely on utility grids for their operation. The growing global efforts to achieve sustainability introduce intermittent renewable energy sources, such as solar and wind, into the power grid, which goes against the reliability principles of the data center industry. As computer technologies further permeate our everyday lives, their energy consumption and environmental impact become greater.

The feasibility study aims to investigate the potential of using hydrogen as a primary energy carrier in data center applications in terms of reliability, efficiency, electrical and hydrogen topology, infrastructure layout, and control strategies. A comprehensive review of commercially available and emerging hydrogen technologies related to storage, transport, electricity generation, and cooling was conducted. Based on this literature review, two designs for a hydrogen data center were developed. A modular approach to the design was proposed, where each module is self-contained and responsible for providing the servers with 1 megawatt of electrical power and cooling.

The first low-temperature design utilizes a hydrogen pipeline with pressure swing adsorption purification supplying hydrogen gas to a cogeneration system. This system combines a low-temperature Proton-Exchange Membrane fuel cell and a direct-fired hydrogen single-stage absorption refrigeration cycle into a single unit to deliver stable power and cooling to the servers. The findings indicate that the overall energy efficiency of this design configuration is high, and the technologies are mature enough to be used today. However, the study identified various technological limitations of purification systems that must be addressed with further research and development. The second high-temperature design eliminates the need for a purification system, relying instead on high-temperature Proton-Exchange Membrane fuel cells coupled to a double-effect absorption refrigeration system. Unfortunately, this design is not feasible in 2024 because the high-temperature fuel cells are in the early stages of development.

A cost analysis was conducted for both designs in the current (2024) and projected (2030) scenarios. The results indicate that at the current level of hydrogen technology development and manufacturing, the operational costs of the low-temperature configuration were comparable to the traditional data centers. However, if hydrogen technology continues to develop according to the projected trends, the proposed designs can achieve up to 50 % cost savings compared to the grid-powered data centers. This research showcases the potential for hydrogen as an energy carrier in data center applications, encouraging further research and exploration of hydrogen technologies.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Abbreviation	Definition
AC	Alternating Current
AFC	Alkaline Fuel Cell
ARS	Absorption Refrigeration System
AI	Artificial Intelligence
CapEx	Capital Expenditures
CCHP	Combined Cooling, Heat and Power
CCS	Carbon Capture and Storage
COP	Coefficient of Performance
CRAC	Computer Room Air Conditioner
CRAH	Computer Room Air Handler
DC	Direct Current
FC	Fuel Cell
HT	High Temperature
HT-PEM	High-temperature Proton-Exchange Membrane
ICT	Information and Communications Technology
IT	Information Technology
LOHC	Liquid Organic Hydrogen Carriers
LT	Low Temperature
LT-PEM	Low-temperature Proton-Exchange Membrane
OpEx	Operating Expenses
PDU	Power Delivery Unit
PEMFC	Proton Exchange Membrane Fuel Cell
PSA	Pressure Swing Adsorption
PSU	Power Supply Unit
ppm	parts per million
PUE	Power Usage Effectiveness
RFP	Raised Floor Plenum
RU	Rack Unit
SLA	Service Level Agreement
SMR	Steam Methane Reformation
TCO	Total Cost of Ownership
UPS	Uninterrupted Power Supply
WUE	Water Usage Effectiveness

Symbols

Symbol	Definition	Unit
F	Faraday constant	C/mol
I_{fc}	Current of the fuel cell	A
$\dot{m}_{\mathrm{H_2,burn}}$	Hydrogen consumption rate of the hydrogen burner	$\mathrm{kg\,s^{-1}}$
$\dot{m}_{\mathrm{H_2,fc}}$	Hydrogen consumption rate of the fuel cell	$\mathrm{kg\,s^{-1}}$
$\dot{m}_{\mathrm{H_2,pure}}$	Mass flow rate of hydrogen prior to purification	$\mathrm{kg\,s^{-1}}$
$\dot{m}_{\mathrm{H_2,pure}}$	Mass rate of the purified hydrogen	$\mathrm{kg\,s^{-1}}$

Symbol	Definition	Unit
$\dot{m}_{\mathrm{H_2O,fc}}$	Water production rate of the fuel cell	$\mathrm{kg\,s^{-1}}$
n_{fc}	Number of fuel cells in the stack	-
$P_{\mathrm{fc,total}}$	Total energy used by the fuel cell during operation	W
P_{IT}	Electricity consumption of IT equipment	W
$\dot{Q}_{\mathrm{burn}}$	Heat transfer rate of the hydrogen burner	W
$\dot{Q}_{\mathrm{evap}}$	Heat transfer rate of the evaporator	W
$\dot{Q}_{\mathrm{fc}}$	Heat transfer rate of the fuel cell	W
$\dot{Q}_{\mathrm{gen}}$	Heat transfer rate of the generator	W
$\dot{W}_{\mathrm{pump}}$	Power of the ARS pump	W
V_{fc}	Voltage of the fuel cell	V
Δh_{HHV}	Higher Heating Value of hydrogen	$\mathrm{MJ\,kg^{-1}}$
Δh_{LHV}	Lower Heating Value of hydrogen	$\mathrm{MJ\,kg^{-1}}$
η_{dc}	Efficiency of the DC/DC power converter	%
η_{fc}	Electrical efficiency of the fuel cell	%
η_{yield}	Recovery rate of the purification process	%

1
Introduction

1.1. Motivation

Data centers are one of the most important technologies in the modern world. They enable ubiquitous connectivity between people and businesses at very low costs. Digitization forces innovation and pushes technological advancements further. Data centers are at the forefront of this progress, allowing the colocation of high-performance computing and networking resources to fulfill ever-growing customer demands. However, rapid progress comes at an environmental cost. In 2016, data centers in the United States handled about 300 million terabytes of data, consuming 8.3 billion kWh of energy, which is approximately 35 kilograms of CO_2 emissions per terabyte of data. [1] The trend is accelerating as dependence on information technology grows, as seen in Figure 1.1.

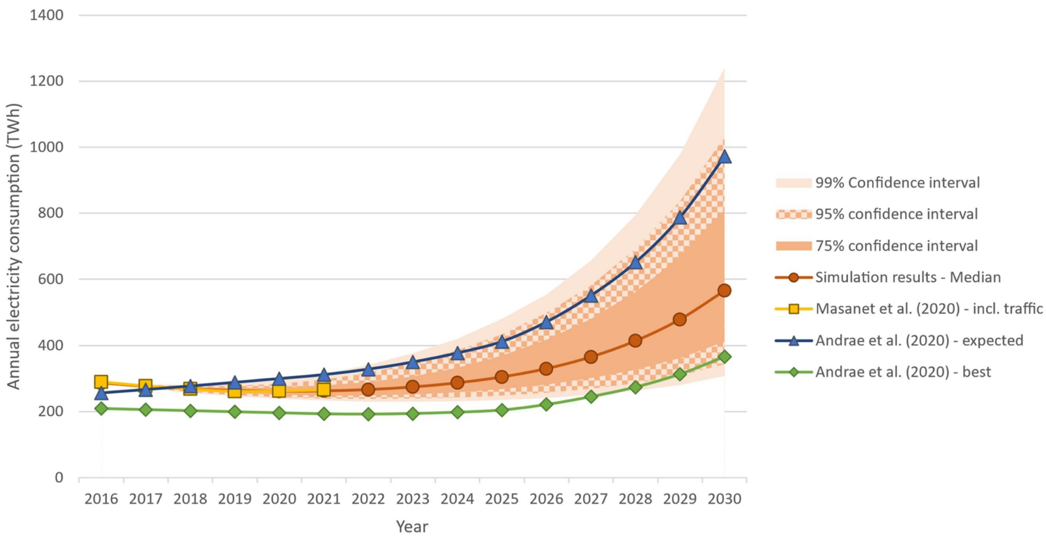


Figure 1.1: Data center energy consumption predictions. [2]

According to the International Energy Agency, data centers are currently responsible for 1 % of global greenhouse gas emissions. [3] This figure is expected to rise to over 2 % by 2030. [2] Although Information and Communications Technology (ICT) companies heavily invest in renewable energy projects, the industry's efforts lag behind the rapid growth. Attempts at sustainability by data center providers are significant for the sustainability industry as a whole. Data centers were the first to implement high-efficiency power and cooling designs. Systems such as free-cooling economizers, low-water usage cooling systems, and solar installations are some of the solutions that address the carbon emission problem. Many data center operators participate in global corporate renewable power purchase agreements, which accounted for half of the global agreements in 2020. [4] These agreements stimulate the economic benefits of early renewable power deployments, as the ICT sector subsidizes them.

1.2. Problem Definition

Addressing the industry's sustainability will require a radical change in infrastructure. Traditional data centers use a power grid connection to deliver electricity and provide cooling to the Information Technology (IT) equipment. Higher density and reliability deployments, known as hyperscale data centers, utilize carbon fuels in their on-cite power plants for power. [5] All modern data centers focus on maximizing energy efficiencies, and the efforts have been effective. However, for the industry to become truly "green," clean and renewable energy sources must be used instead. The current efforts to achieve net-zero emissions use sustainable energy generation techniques such as solar and wind. Unfortunately, these intermittent energy sources violate reliability principles — the primary operational constraint of data centers. Other alternative technologies must be considered in data center applications as industries worldwide are transitioning to clean energy.

The objective of the feasibility study is to explore hydrogen as an energy carrier for power and cooling in data centers. Hydrogen's properties make it relatively easy to transport and store, and if used on a large scale, it could be cost-effective compared to purchasing electricity from the utility grid. Betting early on the potential success of the future hydrogen economy can provide an early technological advantage in the data center industry. The proposed solution has the potential to reduce running costs while eliminating CO_2 emissions.

1.3. Research Questions

This research aims to answer theoretical questions about implementing a data center in the Netherlands' upcoming hydrogen economy. Due to many intangible factors present in data center infrastructure, the answers are by no means complete. Physical prototyping and validation are required to assess the results of this research. The questions are the following:

1. What are the opportunities and challenges of a data center utilizing hydrogen as a primary fuel source for power and cooling while adhering to high standards of reliability and efficiency?
2. How does a hydrogen data center infrastructure compare to existing state-of-the-art data centers regarding energy efficiency, reliability, and costs?
3. What are capital investment and operational costs associated with hydrogen-based data center infrastructure, and are they competitive with existing data center designs?

1.4. Thesis Outline

Chapter 2 will explore technologies and best practices of the existing data centers. The organization of servers, typical infrastructure design, and industry constraints in terms of reliability and efficiency metrics will be explored. Next, Chapter 3 will outline relevant hydrogen technologies applicable to data center infrastructure. An in-depth literature review will be performed on hydrogen storage, transport, electricity generation, and cooling methods. In Chapter 4, two designs of the hydrogen data center will be proposed. The design will be composed of infrastructure component layout, electrical and hydrogen system topology, physical arrangement of components, and operational procedures. Selection of hydrogen technologies will be performed, and commercially available options will be explored. Chapter 5 will perform mathematical modeling of the system. Electricity generation and cooling system will be coupled, and the total hydrogen consumption rate will be determined. Chapter 6 will evaluate the economics of the proposed design in terms of capital investment and operation costs. Lastly, Chapter 7 will conclude the proposed design and evaluate the feasibility of a fully hydrogen data center.

2

Traditional Technologies

Traditional data centers have had many years to develop and improve electrical and thermal systems. Modern state-of-the-art projects concentrate as much computing power as possible into small areas to extract high efficiencies. [6] The rise of colocation — sharing a data center space among multiple companies — has contributed to improvement and standardization in the industry. [6] The rise of cloud computing has further incentivized the industry to move towards the centralization of even more computing resources, leading to what is called hyperscale data centers. [7] With their high energy density and tight integration of infrastructure components, these data centers operate with remarkable efficiencies. The data center industry has developed various standards for organizing, powering, and cooling computing resources. This commonality allows for the portability of developed technologies between hardware vendors, installers, and data center owners. A hyperscale data center is an excellent example of efficient resource utilization. Unfortunately, the source of their energy is predominantly fossil fuels.

This chapter will discuss traditional technologies used in modern data centers. It will explore the organization of a server room and review the design of traditional infrastructure in terms of power and cooling. The industry's reliability metrics will be studied in depth, and electrical system typologies will be assessed.

2.1. Server Room Organization

Arranging high-power servers in small areas is a great challenge. The goal of modern server layouts is to segregate cool and exhaust air. High-density data centers utilize rack, cabinet, and server room layouts. This highly optimized design philosophy is the focus of the server room organization strategy.

2.1.1. Rack Servers

RU (Rack Units) or simply U (Units) is a standardized measurement of the height of the server, with each U measuring 1.75 inches tall. [8] Some servers may be taller and occupy, for example, 4U or 7 inches. [8] An image of different server racks can be found in Figure 2.1. The dimensions of the racks are standardized globally as IEC 60297 standard. [9] These standards recommend width and depth for easy integration between manufacturers and installers. A typical width is 19 inches, and a typical depth is 36 inches. [10] The server racks are usually assigned a specific role and are responsible for either data storage, processing, or transport. [11] The thermal requirements of each type of server are different, but in general, fans are installed inside the server to push the air through the electrical components. [12]

2.1.2. Racks

Racks and cabinets are also standardized and designed to fit servers of IEC 60297 specifications. A minimum height of 48U is recommended to maximize horizontal space. [13]. The role of the rack or cabinet is to install the servers conveniently, as well as to provide power and networking. Cabinets differ from racks as they provide an additional level of security by encapsulating the servers in a closed frame.

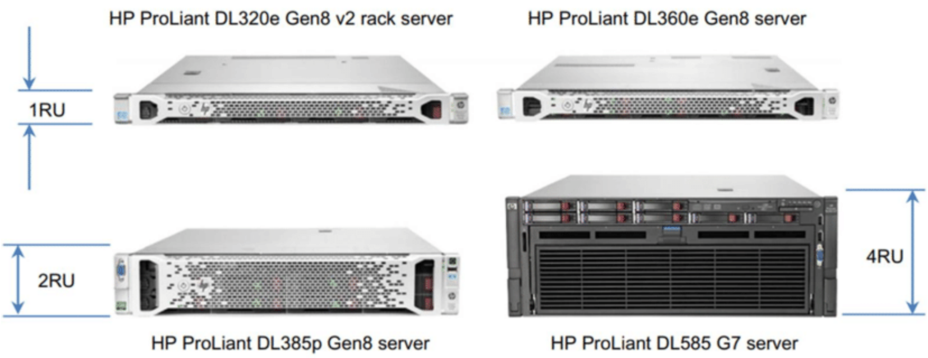
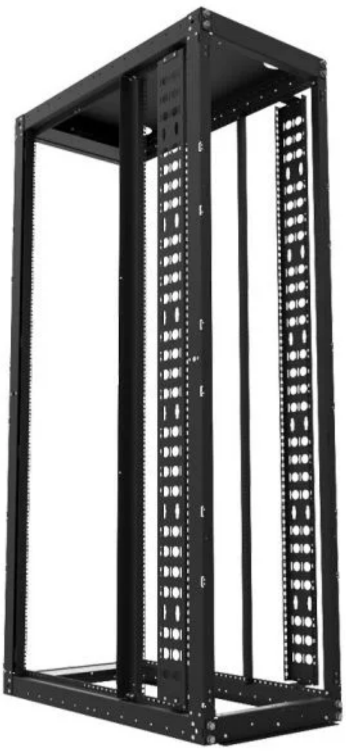


Figure 2.1: Rack servers of different sizes. [8]

Figure 2.2 demonstrates the difference between racks and cabinets. Standardized mounting layout allows for installation of rails — easing maintenance of installed servers. Usually, each rack houses power delivery gear at the lowest level and networking gear at highest levels. [13] This uniform design philosophy is utilized to homogenize the routing of resources. The power and networking supporting hardware are also packaged as standard U-Rack servers. By following these design principles, data center operators can arrange compute resources most optimally. Expansion of the data center capacity is easier when such rules are in place.



(a) Rack [14]

(b) Cabinet [15]

Figure 2.2: Rack and cabinet.

An increase in the energy density of racks creates difficulties for data center design. The average power density per rack has grown from 2.4 kW in 2011 to 8.4 kW in 2020. [10] The increasing demand for artificial intelligence has boosted power consumption per rack to 40 kW or more. [10] Uptime Institute defines rack density zones to assist in the appropriate cooling system selection, available in Table 2.1. [12] The internal workings of these servers are left as an exercise for the reader as they are outside of the scope of this study. However, it is essential to understand these compact computer systems' thermal properties to address cooling challenges.

Classification	Power per rack (kW)	Power density (W/m^2)
Low density	< 0.6	< 215
Medium density	0.6 – 1.2	< 430
High density	1.2 – 3.3	< 1184
Ultra-high density	> 4.0	> 1432

Table 2.1: Rack density definitions. [12]

2.1.3. Server room

On a grand scale, clusters of data center cabinets are encapsulated into separate rooms, each operating independently. These rooms are designed for predicted electrical and thermal loads based on the server hardware specifications. The primary goal of room organization is to control temperature and humidity. [16] The secondary consideration is to filter out environmental contaminants and direct airflow in specific ways. [16] Lastly, the room arrangement model provides a layer of physical security. [16]

In a typical deployment, multiple air conditioning units are installed in each room. The optimal strategy for room-based cooling is to direct airflow most efficiently. [7] Modern designs segregate the intake and exhaust of the server racks because significant efficiency losses are incurred when the hot exhaust is mixed with the cool intake. Operating expenses can be reduced by 10 – 30 % with proper airflow design. [7]

The most common method of organizing the thermal flow is the raised floor plenum (RFP) hot aisle/cold aisle configuration. [13, 17]. This method is widely used in the industry to optimize cooling performance. [17] Visualization of this approach is presented in Figure 2.3. This cooling method heavily utilizes the difference in density between hot and cold air. The racks are arranged in rows with alternating orientations to segregate the hot and cold temperature zones. Fresh cool air enters the cold zones from under the floor through perforated tiles. The hot air is collected from a high point of the hot zone. The constrained cooling flow prevents chilled air from mixing with exhaust, improving efficiency.

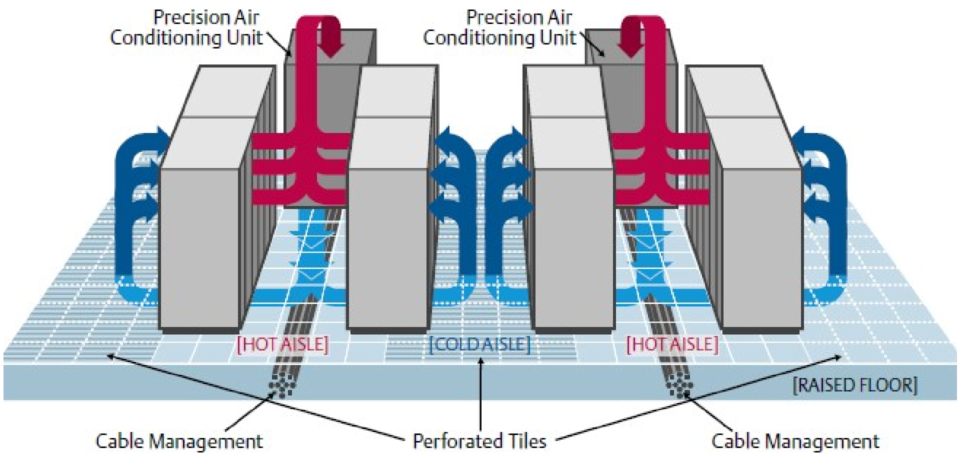


Figure 2.3: Raised floor plenum hot-aisle/cold-aisle server room configuration. [13]

2.2. Infrastructure Design

The structure of a traditional data center is outlined in Figure 2.4. The key components of the electrical system are the utility power grid, backup generators, a power switch, an uninterruptible power supply (UPS), and power delivery units (PDUs). [11] The cooling system comprises a chiller, cooling tower, and an optional economizer. [11] All non-renewable data centers utilize grid connection as a primary source of energy input. In the case of high-reliability data centers, multiple grid connections are used. [5] The power switch, commonly known as an automatic transfer switch, maintains a stable power output from one of the available sources. [5] Once energy enters the data center, it is directed toward the two subsystems of IT equipment: power and cooling. Generally, 45 % of energy is used by the IT equipment and 38 % by cooling systems. [11] Ancillary building services cater to the staff that oversees the daily operation, including security systems, air-conditioning offices, and lighting. [18] The breakdown of energy use of a typical data center can be found in Figure 2.5.

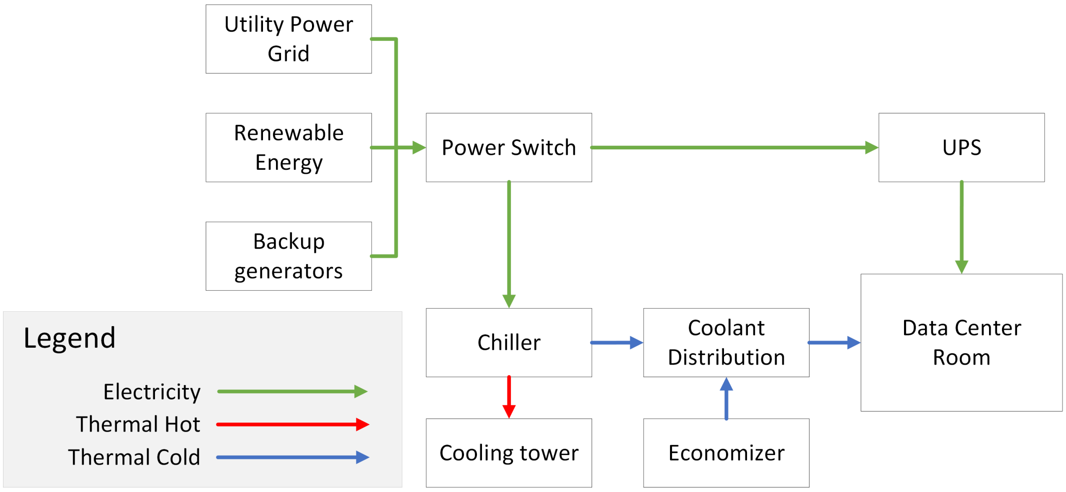


Figure 2.4: Infrastructure component diagram of a traditional data center. [11]

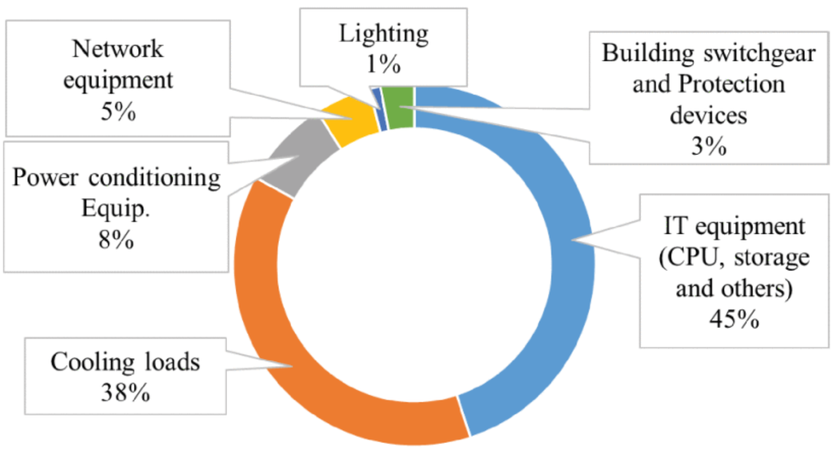


Figure 2.5: Power consumption breakdown of a typical data center. [11]

There is a large variety of different configurations depending on the deployment specifications, each ensuring a certain degree of reliability. The most common method of strengthening this metric is to deploy diesel backup generators and robust UPS systems. [5] In case of a grid malfunction, the UPS picks up the power spike while the diesel generators are powering up. [19] In theory, the data center can run for extended periods as long as the backup fuel is supplied. A large bank of lead-acid batteries is usually used to absorb the initial power spike on grid disconnection. [19] Typically, the batteries have enough capacity for 15 minutes of outage. [16] The diesel generators are a vital part of running cloud services reliably. According to Microsoft, diesel generators, on average, are used once every year during an outage. [20] There is a significant cost associated with maintaining expensive equipment, which is mostly idle. [20] Elimination of these components in data centers can improve operational costs.

Transitioning traditional data centers to sustainability is a significant challenge, with the U.S. government classifying data centers as wave 3 of the hydrogen transition roadmap — a priority similar to hospitals.

[21] It is suggested that the wave 3 transition should occur after the technology has matured and is thoroughly tested in other industries. [21] However, the eventual transition to fully renewable fuels is inevitable. Understanding and reusing existing data center technologies can simplify this transition by building on top of decades of operational experience.

2.2.1. Electrical System

The electrical system, commonly called the power conditioning system, is at the core of data center operation. Before the energy from the grid is supplied to the individual server racks, it must be cleaned and converted to proper voltages. Power conditioning is achieved through the use of Uninterruptible Power Supply (UPS), Power Supply Unit (PSU), and Power Delivery Unit (PDU). [11] A diagram of the power flow of a traditional data center is outlined in Figure 2.6.

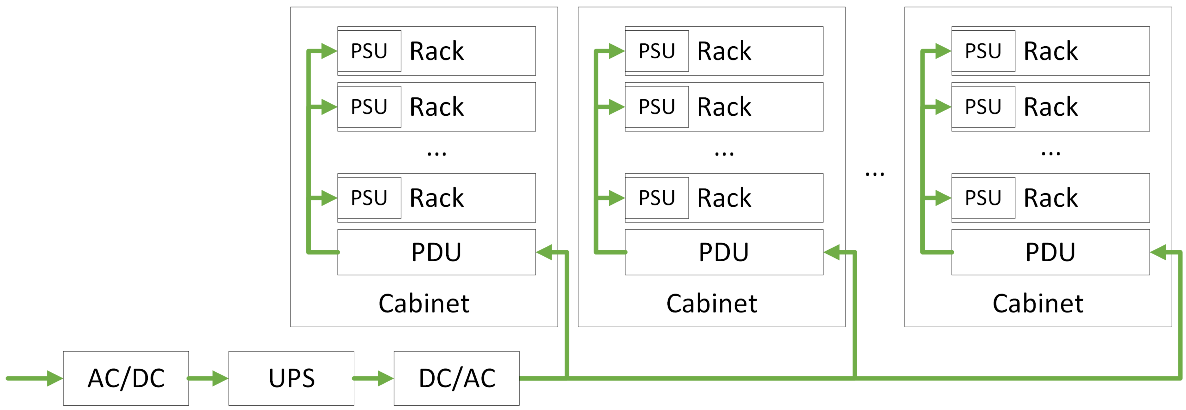


Figure 2.6: Power conditioning system.

Uninterruptible Power Supply

An uninterruptible power supply is one of the most important components in the electrical system of a data center. UPS addresses issues with electricity delivered by the grid or backup generators. Electricity from the primary switch may contain the following bad qualities: interruptions, impulsive transients, under-voltages, over-voltages, phase-desyncing, and harmonic distortion. [22] As the UPS buffers incoming power, it addresses all these issues and protects the IT equipment. [22] Typically, the UPS is sized to power the entire data center for 15 minutes. [16] However, in most cases, during an outage, they are used for only 30 seconds - the time it takes for diesel generators to reach full power. [20] Since traditional data centers rely on the three-phase electrical grid, AC power must be consumable and producible by the UPS. Double power conversion from AC/DC and DC/AC incurs significant power losses, especially when the IT load is low. [23] Synchronization and correction of phases are difficult, significantly increasing equipment costs. [23] Some data center designs, namely Google's "Customized Server," utilize a DC bus design to avoid inefficiencies and decrease costs. [23]

Power Delivery Unit

The power delivery unit distributes power to many server racks inside the cabinet. PDU acts like a sophisticated power strip. It is common for this device to measure the power usage of each server and report it to the control system. [24]

Power Supply Unit

The power supply unit is the last step of power conditioning. This power converter is located inside the server rack. It converts high-voltage AC into DC power for the server hardware. High-voltage AC power is used throughout the power conditioning system for efficiency benefits, as resistive current losses are minimized. [25] The incoming AC can be 1 or 3 phases, and the voltage varies depending on the country, with typical values of 120 V or 208 V in North America and 230 V or 400 V in Europe. [25] The output of PDU provides higher currents at standard server component voltages, with typical values of 12 V and 5 V. [26]

2.2.2. Cooling System

The data center's cooling systems ensure that the IT equipment operates optimally. Proper is essential to fulfill the reliability, efficiency, and longevity requirements. [27]. The cooling system operates by moving the heat from the server room into the outside environment using a vapor-compression refrigeration cycle. [28] The principles of operation are the same as residential air conditioners, with extra focus on precision and reliability. [28] This specialized air conditioning equipment is commonly called a "precision cooling system." Large-scale data centers implement either water-cooled or chilled water designs. An economizer can also be installed to lower energy requirements. [26]

Water Cooled

Water-cooled systems utilize a refrigerant to maintain the desired temperature and humidity within data centers. The system is made of three components: The Computer Room Air Conditioner (CRAC) unit located inside the IT environment, the pump package inside the mechanical room, and the cooling tower mounted on the roof. [27] The CRAC unit draws warm air from the servers, cools it through refrigeration coils, and recirculates the cooled air. [27] Many of these units are connected to the pump package, which transports the heated refrigerant to the cooling tower. The cooling tower then dissipates the waste heat into the external environment.

This cooling solution offers some advantages, such as high reliability and ease of installation. [29, 27] However, these benefits also come with significant drawbacks. The system is expensive to install and has very high maintenance costs while consuming large quantities of water. [29, 27] The water consumption is due to the use of evaporative cooling in the cooling tower. Each CRAC can sustain a cooling load of 35 – 150 kW. [28]

Chilled Water System

Chilled water systems operate on a different principle as they use a central chiller and a Computer Room Air Handler (CRAH) unit. [27] The chiller in the mechanical room contains a complete refrigeration system. The cooled water from the chiller is then supplied to the CRAH units. Unlike CRAC units, CRAH units are passive components without any moving parts. [27]

Centralization of refrigeration offers several benefits. The overall system is cheap and can support a large number of CRAH units, making this system ideal for large-scale installations. [27] Unfortunately, it is not a good choice when high reliability is a priority. This design creates a single point of failure and is more prone to mechanical malfunctions. [27]

Economizer

Economizers are another important efficiency-optimization component of a data center. The idea behind the economizers is that the outside environment can be used instead of a cooling system when the temperature outside is sufficiently low. [30] The outside environment must be suitable for the economizer to affect the minimization of cooling system use significantly. [30] Some Nordic countries have optimal climates where the data center uses an economizer exclusively for cooling. [30] Airside and waterside are two types of economizer systems, each offering its own set of advantages and disadvantages. [30]

The airside economizer draws cold air from the outside to the data center room. However, the outside air must be processed to correct humidity and quality standards. [30] Filters are in place to avoid contaminants that can damage IT equipment. This type of economizer is recommended for locations with stable temperature and humidity profiles. [30]

Waterside economizer operates on a different principle. It indirectly cools the servers, using outside air to reduce the temperature of the chilled water. [30] This cooling strategy is known in the industry as "free cooling" because, in favorable climates, the chiller is bypassed completely, resulting in large cost savings. [31] The costs of producing chilled water can be reduced by up to 70 %. [31]

2.3. Reliability

Data centers are a crucial component of the modern interconnected world. Many critical infrastructures, such as healthcare, government, public transport, and communications, depend increasingly on computing services provided by data centers. To ensure the stable operation of these industries, data centers must operate reliably with minimal downtime. The reliability of data center infrastructure can be estimated using various metrics and calculated by operational performance measurements. [26] Infrastructure designs are then classified into tiers based on their reliability ratings.

2.3.1. Reliability Metrics

Reliability metrics are essential to quantifying the performance of the data center. Firstly, they provide insights into the consequences of interruptions in terms of frequency, duration, or extent of outages, enabling data center operators to optimize the quality of IT services. [26] Secondly, these metrics also serve as benchmarks for performance, enabling quantitative comparison between different data center designs. Lastly, reliability metrics are used as compliance tools, as the clients occupying the data center must satisfy their own criteria and regulations. [26] Software companies cannot guarantee operational compliance to their clients without strong reliability guarantees at the physical server layer. [26]

The most common system-wide metric indices are SAIDI, SAIFI, CAIDI, and CAIFI. [26] These metrics aim to quantify the undesirable effects of failures on system and customer level in terms of duration and frequency. The summary of these metrics is provided in Table 2.2.

Service Level Agreements (SLAs) are a common practice in the ICT sector to enforce reliability and availability requirements. [11] Specifically, SLA is a contract between the service provider and a customer in terms of the level of performance, operational uptime and any of the aforementioned metrics. [32] These agreements hold the data center accountable for downtime exceeding the advertised end-user availability. [32] Also, they set tenant expectations; SLAs enable enterprises to guarantee their commitments to their customers. Failures can have severe cascading effects, as data center reliability is the foundation of all online businesses.

Metric	Computation	Description
System Average Interruption Duration Index (SAIDI)	$\frac{\text{sum of all customer interruption durations}}{\text{total customers in the system}}$	Average annual outage time per utility customer
System Average Interruption Frequency Index (SAIFI)	$\frac{\text{number of customer interruptions}}{\text{total customers in the system}}$	Average annual number of interruptions per utility customer
Customer Average Interruption Duration Index (CAIDI)	$\frac{\text{sum of all customer interruptions}}{\text{number of customer interruptions}}$	Average interruption duration.
Customer Average Interruption Frequency Index (CAIFI)	$\frac{\text{number of customer interruptions}}{\text{customers with at least one interruption}}$	Average number of interruptions for customers experiencing an interruption.

Table 2.2: Common reliability metrics. [26]

2.3.2. Tiers

In data center reliability certification, tiers are the most prevalent metric. This metric is part of the ANSI/TIA-942 standard from the Telecommunications Infrastructure Standard for Data Centers. [33] Clear requirements and certification procedures are implemented to unify reliability measurements. That means when a company refers to a tier IV data center, they guarantee a fault-tolerant operation with five nines of availability, allowing for 76 seconds of downtime per year. [11] The tier specification is not a definitive guide for infrastructure implementation but a template for achieving certain operational stability. [5] Since data centers are custom-built, each one of the deployments should be certified by an independent third party. [5] The specification recommends counts of electrical and mechanical system components such as grid connections, backup generators, UPS, and cooling systems. Table 2.3 summarizes all tier requirements.

There is a significant difference between component and end-user reliability ratings. Component reliability refers to hardware resilience to failure of any system component for recommended layouts of IEEE Standard 493-2007. [34] The standard assumes that the overall rating for the data center is as reliable as the minimum reliability rating of each component. [34] Therefore, component reliability is a purely theoretical computation that encompasses the failure rates of the hardware components organized in standardized electrical topologies with component counts as listed in Table 2.3. In practice,

	Tier I	Tier II	Tier III	Tier IV
No. of utility supplies	1	1	1+1	2
No. of backup generators	Optional	N	N+1	2N
No. of UPS	N	N+1	N + 1	2N
No. of mechanical systems (cooling)	N	N+1	N+1	2N
Component availability	0.999 947 0	0.999 951 2	0.999 979 1	0.000 007 6
End-user availability	0.9967	0.9975	0.9998	0.9999
Maintenance	outage for maintenance	outage for maintenance	concurrently maintainable	fault tolerant

Table 2.3: Comparison between different tiers of reliability. [5, 34]

the reliability ratings are lower as they consider human error and planned maintenance. [34]

In Table 2.3, terms such as N+1 (need plus one) or 2N (double need) represent the component counts. [5] In need plus one configuration, "N" refers to the count of components that share the full load, and "+ 1" specifies that one redundancy is on standby, ready to take over operation when other component fails. [22] Higher redundancy is possible; for example, N + 2 allows for two components to fail, enabling concurrent maintenance on the system without total shutdown. An illustration of this concept with respect to a UPS subsystem can be found in Figure 2.7. With higher reliability goals, double need configuration requires two separate distribution paths to be present. [5] As a result, the whole UPS system can fail because another one has full capability to take over and fulfill the power demands. An excellent example of a "2N" configuration is a power distribution system. The server is always connected to two separate UPS subsystems through two redundant PDUs. [5]

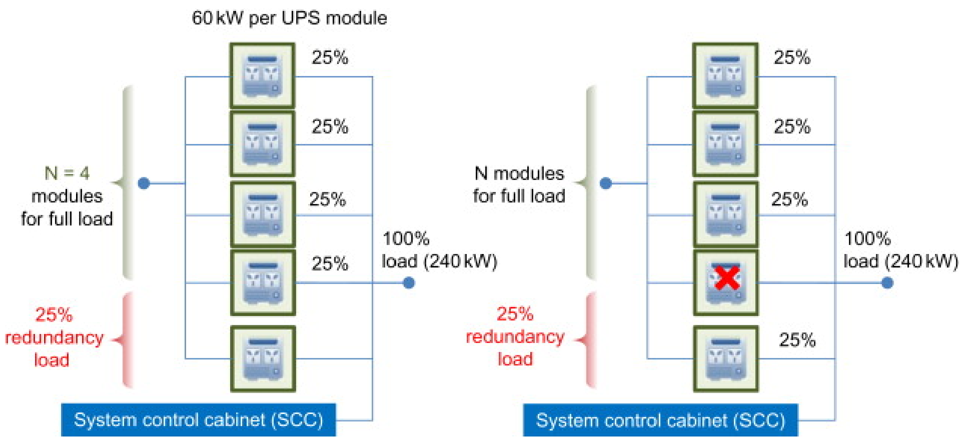


Figure 2.7: N+1 configuration example for UPS subsystem. [22]

A data center certified to the highest reliability tier IV requires a redundant cooling source with critical components running through a fault-tolerant electrical supply. [5] Two electrical subsystems must power each server. Because hardware is over-provisioned, maintenance can be performed without interrupting operation. [11] Every single mechanical and electrical component like pumps, fans, power switches, wiring, UPS, and PDU, needs to be connected in a way to satisfy peak load when another half of the components fail. [34] Critical components such as fluid pumps must always run on stable power through the UPS.

Figure 2.8 illustrates the electrical system topology, showcasing the redundancy of systems designs to account for an inevitable failure of hardware. The diagram indicates primary connection paths with solid lines and redundant connectivity with dashed lines. Automatic failover guarantees stable operation during unexpected faults or planned maintenance. Figure 2.8 demonstrates the intentional split of the infrastructure into two halves. The halves are "interwoven," operating at half capacity each. The Uptime Institute suggests that international companies in E-commerce, market transactions, and finance best fit this reliability tier criteria. [5] Over provisioning of hardware, no matter the cost, is a needed sacrifice, as these businesses run software designed to operate 24/7, and downtime can have serious financial or legal consequences.

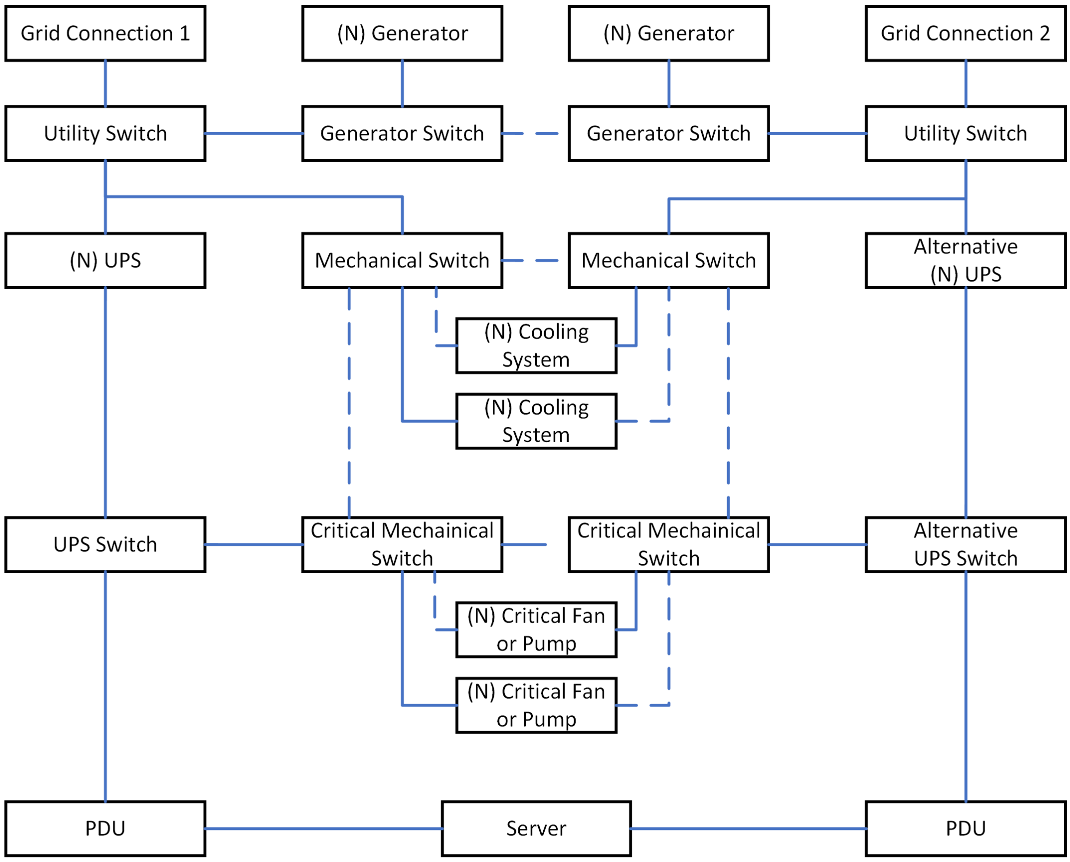


Figure 2.8: Electrical system topology of tier IV data center. [5]

It is also essential to consider sacrificing reliability to cut costs. Lower-reliability data centers cater to firms that do not solely rely on IT infrastructure or use web presence as a passive marketing tool. [5] Data centers at the lower tier do not even have to employ backup generators and must go offline during maintenance. Figure 2.9 illustrates the simplicity of the architecture, especially when compared to Figure 2.8.

2.3.3. Thermal environment

Properly cooling the IT and infrastructure equipment presents challenges related to reliability. As the density of server racks increases, maintaining optimal temperature and humidity becomes more challenging. Failures in thermal control can cause erratic or unrepeatable errors, high soft error rates, and hardware failures. [12] Soft errors are particularly damaging for online businesses as correct software fails when running on deteriorating hardware. [12] Therefore, temperature and humidity must be controlled at all times to prevent unexpected failures.

Excessive temperatures cause hardware to activate protection mechanisms and throttle their performance. On the contrary, over-cooling can lead to dew formation, increasing the chances of short-circuit. High humidity may lead to printed circuit board failures. [12], while low humidity increases the chance of static electric discharge. [29] Even when temperature and humidity ranges are maintained, thermal fluctuations can cause issues. [12] Excessive expansion and contraction of the materials inside the computers can cause premature hardware failures weeks or even months later. [12] Diagnosing these issues is complicated. Therefore, a proactive approach to thermal management must be taken.

ASHRAE Technical Committee 9.9 publishes thermal guidelines for recommended temperature and humidity ranges in the data center, available in Table 2.4. The specification defines a set of class zones

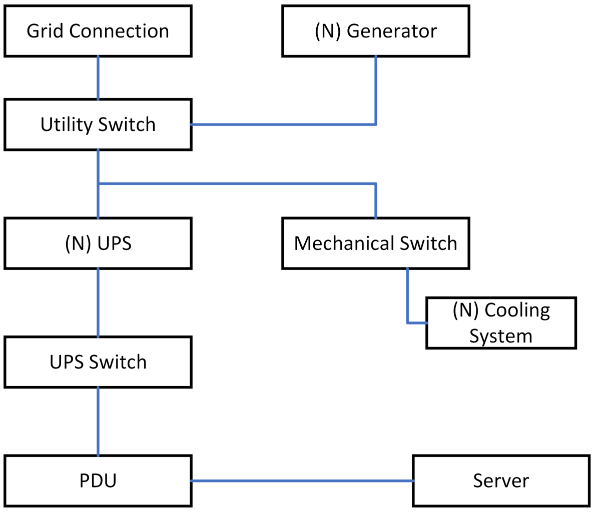


Figure 2.9: Electrical system topology of tier I data center. [5]

representing different levels of strictness regarding the thermal environment. Class A is the most stringent, defining the tightest temperature and humidity ranges while requiring uninterrupted cooling. [12] Class A can only be achieved with high-reliability data centers of certification tier III or above, as cooling load must be satisfied during an outage or chiller failure. [12] Cooling components like fans and pumps must be operated on the critical power system running on the UPS, which is not required for tier I and tier II certifications. [12]

Like the tier specifications, lower thermal reliability classes are also defined, as some businesses can tolerate the uncertainties. In turn, operating a data center at the lowest recommended thermal Class C reduces cooling expenses significantly. [12] In some cases, economizer cooling is sufficient, resulting in zero-cost cooling. [12]

	Class A	**Class B**	**Class C**
Dry-Bulb Temperature (°C)	18-27	5-35	5-40
Relative Humidity (% rh)	60	8-80	8-80
Classification	Uninterruptible	Continuous	Interruptable

Table 2.4: Cooling zones of ASHRAE 2015 Thermal Guidelines. [35, 12]

Thermal guidelines for data centers have undergone significant changes, with newer standards allowing for higher operational temperatures. [30] Data center operators have found that running IT and infrastructure systems at higher temperatures can significantly reduce cooling requirements. [30] Oracle found that increasing temperature by 1 °C reduces energy bills by 4 %. [30] Google has run its servers at elevated temperatures for a long time now, utilizing this strategy to stay ahead of competitors regarding sustainability metrics. [36] They report that raising the temperature by 2 – 4 °C reduces energy consumption between 20 and 28 %. [30]

2.4. Efficiency Metrics

Data centers aim to improve operational efficiency to reduce costs and environmental impact. Reliable and uniform performance metrics are a powerful industry tool, leading to many innovations and improvements. These efficiency measurements, metrics, and reporting conventions are guided by a group of leaders across the industry, spanning large corporations, certification bodies, and government agencies. [18] The two main metrics of concern are Power Usage Effectiveness (PUE) and Water Usage Effectiveness (WUE).

2.4.1. PUE

Power usage effectiveness is a metric for characterizing and reporting overall data center infrastructure efficiency. [18] It is calculated on annual data and includes all energy types such as electricity, natural gas, and consumption of chilled district water. [18] In mathematical terms, PUE is total data center energy consumption divided by IT energy consumption. [18] The goal is to achieve a value close to one, meaning all used energy was spent on running the servers. Values above one signify losses during operation, where cooling and supporting infrastructure are typically the biggest contributors. [18]

Unfortunately, this metric has its criticisms. Energy usage information is proprietary data that the companies strictly guard. [37] Lack of transparency and incompatibilities between measurement techniques of different companies make it challenging to asses and verify reporting. [37] Additionally, this metric cannot be used for sustainability measurements, as research does not show a strong correlation between emission performance and PUE. [38]

Google is an exemplary company when it comes to the sustainable design philosophy and use of PUE metrics for continuous efficiency improvements. In 2024, Google reported an average 12-month PUE score of all their data centers of 1.09 — a significant improvement from the value of 1.20 in 2009. [36] For every 1 kW of server electricity consumption, only 90 W of energy was used to support the operation. This figure is impressive compared to an estimated industry average of 1.98 in 2011 and 1.55 in 2022. [39]

PUE scales different energy sources by a weighting factor, allowing for the calculation of an equivalent PUE for the proposed hydrogen data center. A scaling factor of 0.3 should be applied when hydrogen is used as a fuel. [18] Unfortunately, the PUE of a hydrogen data center cannot be determined with certainty before construction. Measurements from the running data center are required for accurate evaluation. [18]

2.4.2. WUE

Water usage effectiveness is defined as annual water usage divided by the total IT energy usage. [40] The units of WUE are in liter per kilowatt-hour. [40] The U.S. national average WUE of data centers is 1.8. [40] Using the average WUE, a 1-megawatt data center has water demand of about 15 million liters per year.

Cooling towers are a major contributor to data center water usage. Industrial cooling towers operate on the principle of latent heat of vaporization of water. They consume large amounts of water because the heat is dissipated by evaporating water. [41] Regardless of the operating efficiency, approximately 1.8 gallons of water are evaporated for every ton-hour of cooling. [41] Converting to metric units results in 1.9 liters/kWh. Other effects of the cooling towers, such as bleed-off and drift, further increase the water usage requirements. [41]

The ICT sector is taking initiatives to minimize water usage's economic and ecological impacts in data centers. Google aims to replenish more water than it consumes through the water stewardship program. [42] The goal is to replenish 120% of the freshwater consumed across their offices and data centers by 2030. Unfortunately, Google and other data center companies do not publish WUE metrics of their data centers.

3
Hydrogen Technologies

Hydrogen is the most abundant chemical element in the universe, and if used as a fuel, it has a lot of potential to drive the sustainable economy of tomorrow. [43] From a chemical perspective, hydrogen is a unique molecule. Its heating value is three times higher than petroleum, which makes it, in theory, the best fuel to transport and generate energy. [43] Hydrogen is suitable for data center applications because it has the same properties as electricity: it can be transported and stored relatively easily. This chapter will provide an overview of hydrogen as an energy carrier. Commercially available and emerging methods of production, storage, transport, purification, electricity generation, and cooling will be discussed.

3.1. Production

A report by the Hydrogen Council, a group of 145 companies aiming to transition to clean energy through hydrogen, expects tremendous growth in the coming years. [44] Figure 3.1 shows the planned production capacity of electrolysis projects, which aim to generate over 300 GW of green hydrogen by 2030, with a total investment of $570 billion up-to-date. [44]

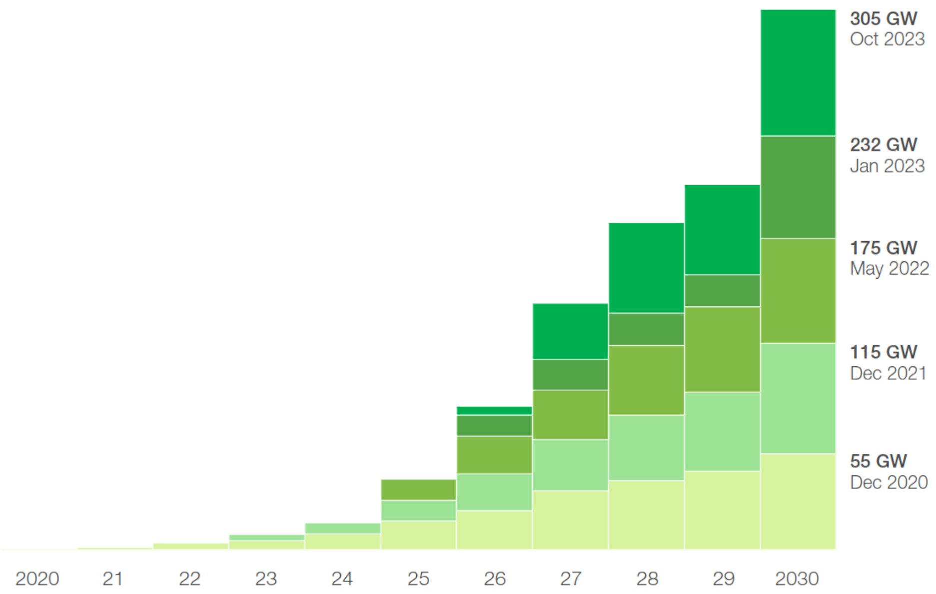


Figure 3.1: Global announced cumulative electrolysis capacity. [44]

The report focuses on green hydrogen, which has no carbon emissions. However, not all hydrogen is equal in terms of environmental impact. There are many different ways of producing hydrogen for use in industrial applications. The industry classifies these methods in terms of color.

3.1.1. Colors

The color of hydrogen is directly tied to the fuels used and production methods. Table 3.1 outlines the most common manufacturing techniques and their related colors.

Color	Fuel source	Production process	CO_2 emissions	Efficiency (%)
Black	Coal	Gasification	High	35
Gray	Natural Gas	Steam reformation	Medium	74 – 85
Blue	Natural Gas	Steam reformation + Carbon capture and storage	Low	74 – 85
Green	Water + renewables	Electrolysis	Minimal	70
Pink	Water + nuclear	Electrolysis	Minimal	70

Table 3.1: Hydrogen color spectrum. [45, 46]

Black Hydrogen

Black hydrogen is the least environmentally friendly option for hydrogen production. The gasification production method suffers from low efficiencies and very high CO_2 emissions. [46]

Gray Hydrogen

Grey Hydrogen is produced through a process of Steam Methane Reformation (SMR). [45] Natural gas is used as a feedstock, producing hydrogen and byproducts by splitting methane in a high-temperature reformation process. SMR is a mature and commonly used method for hydrogen production, accounting for more than 80 % of worldwide hydrogen. [46]

Blue Hydrogen

Blue hydrogen production uses the same process as gray hydrogen. However, the emissions are reduced using Carbon Capture and Storage (CCS) technology. [45] Captured greenhouse gases are stored underground, resulting in a clean but not sustainable hydrogen fuel source. [45]. Blue hydrogen is a good fuel during the transition to clean and renewable hydrogen economy. However, the CCS process is imperfect as some CO_2 escapes into the atmosphere. [46]

Green Hydrogen

Green hydrogen is also known as renewable hydrogen. It is produced from water using an electrolysis process. [45] This process uses electrical power from renewable energy sources such as solar and wind to split the water molecules into hydrogen and oxygen. [45] Green hydrogen is a holy grail of sustainability as it produces no greenhouse emissions, albeit at a low efficiency [45] Currently, the deployment of renewable energy is small; therefore, this production method is relatively expensive. [45] Green hydrogen makes up a small percentage of global hydrogen production, but it is expected to change as renewable energy prices fall in the coming years. [45] U.S. Department of Energy speculates that hydrogen produced from electrolysis will be the cheapest in the long run. [21]

Pink Hydrogen

Pink hydrogen is produced using the same electrolysis method as green hydrogen, but a nuclear power plant supplies the electricity. [45] Stable power production of a nuclear power plant is a good fit for continuous electrolysis applications. Pink hydrogen can greatly assist in transitioning to a fully renewable hydrogen economy.

3.2. Storage

Hydrogen is a physical energy carrier that can be stored inside physical containment structures, unlike electricity. This makes hydrogen storage a much cheaper alternative to electrical batteries. Even though a third party would provide hydrogen through perpetual contracts, maintaining backup for higher reliability is essential. A sizable buffer should be sufficient to deal with malfunctioning supply chains and allow the data center to operate during disruptions in the supply chain. An overview of available technologies is outlined in Table 3.2.

Property	**Compressed (70 MPa)**	**Metal Hydride**	**Organic Liquid**
Volumetric Energy Density (MJ/L)	4.9	13.2 – 13.7	5.68 – 6.72
Gravimetric Energy Density (MJ/kg)	6.84	2.28 – 9.12	7.44
Gravimetric Hydrogen Density (wt%H_2)	5.7	1.9 – 7.6	6.2
Release Temperature (°C)	-	250	200 – 400
Storage Temperature (°C)	25	25	-
Waste Heat of Release (kJ/molH_2)	-	119	67.5
Added cost ($/kg)	0.15 – 0.60	0.40 – 4.0	-

Table 3.2: Overview of hydrogen storage technologies. [47, 48]

3.2.1. Compressed Hydrogen

The most compact and economical way to store hydrogen is by using high-pressure storage tanks. [49] Data centers can safely store these tanks near the supply side. To store sufficient amounts of energy, hydrogen needs to be compressed during storage and decompressed before use. Both of these steps require work and, therefore, introduce efficiency losses. [49] Unfortunately, hydrogen gas does not compress linearly and requires more energy to increase pressure to higher levels. Therefore, it is reasonable to use a lower pressure to achieve less losses due to compression. To facilitate dense storage, the size of the tanks is limited to small volumes, and advanced materials like carbon fiber and glass fiber-reinforced plastics are required. [47] The storage tanks are a mature technology with widespread use in the hydrogen economy.

3.2.2. Metal Hydride

Metal hydride storage is a technology that utilizes inter-metallic compounds that store hydrogen atoms inside unstable-hydride-forming elements. [47] Most common hydrides include MhH_2, AlH_3, $LaNi_6H_6$. [47] These technologies offer high volumetric energy density, as the metals can store a lot more hydrogen on the atomic level than other storage technologies. [47] Unfortunately, tight packing of atoms and rearrangement of crystalline structures during discharge introduces a lot of resistance. Removing hydrogen from hydride tanks emits a sizable amount of waste heat, resulting in low round-trip efficiency. [47, 49] High volumetric density is a benefit for mobile applications where storage space is limited. However, it has little benefit to data center deployments. High costs, slow discharge rates, high release temperatures, and relative immaturity of the technology make metal hydride undesirable in data center applications. [47, 49]

3.2.3. Liquid Organic

Liquid organics are also known as Liquid Organic Hydrogen Carriers (LOHC), where hydrogen is stored chemically in organic molecules deficient in hydrogen. [49] Most common LOHC compounds are toluene, cyclohexane, and naphthalene. [47] This technology demonstrates high density in terms of volume and weight. However, its liquid form makes it a good candidate for transport rather than stationary storage. High release temperature and complex chemical processing required to extract energy make LOHC a poor candidate for hydrogen storage in data centers.

3.3. Transport

Data centers, like any large-scale industrial business, require a large volume supply of energy. Traditionally, the power grid was the only choice for delivering electricity. In the case of a fully hydrogen data center, supply logistics are more difficult. The hydrogen industry is not very developed, but a few options are available today. Hydrogen is a highly dense fuel that can be transported in a compressed or liquefied form. [50] The available delivery methods are gaseous tube trailers, cryogenic liquid tanker trucks, or pipelines. [50] Economically, the scale and location of the production site play a significant role in the costs for hydrogen consumers. [50] Available delivery methods are outlined in Table 3.3.

	Truck, gaseous	Truck, liquid	Pipeline
Total Cost ($/kg/100km)	0.5 – 2.0	0.3 – 0.5	0.10 – 1.00
Capacity	400 per truck	4000 per truck	100 000 kg/h
Transport range	Short	Short	Short to long
Efficiency (%/100km)	94	99	99.2

Table 3.3: Overview of hydrogen transportation technologies. [51]

3.3.1. Truck Delivery

Truck delivery is one of the most versatile and common methods for transporting hydrogen. The flexibility and wide variety of stored fuels make it viable for continuous small-scale deployments and emergency delivery.

In gaseous hydrogen delivery, hydrogen is transported as pressurized gas inside tank bundles. This method is suitable for smaller quantities and has been previously used by Microsoft in experimental backup systems. [20] The demand for a 48-hour storage system is low, making this the simpler option. However, at large scales, the throughput is limiting. Research suggests that this method makes short-distance continuous small-scale deployments and emergency delivery feasible. [52] Efficiency of 94% is achieved when fuel consumption by the truck is accounted for.

Hydrogen can also be transported in chemical forms though LOHC. They are stable compounds, making them less insusceptible to leakage. [52] Large quantities can be delivered at once, and the hydrogen can be extracted on site via cracking. These delivery methods have only been use for long distances and very large quantities. [52]

3.3.2. Pipeline Delivery

The pipeline delivery method has low running costs and very low variable expenses. [52] Research estimates total transmission cost at about $0.1 – 1 for a kilogram of hydrogen per 100 kilometers with high transport efficiency of 99.2 % [52] The small efficiency losses are due to compressors maintaining internal pressure, which acts as a short term storage, eliminating the need to buffer incoming hydrogen on-premises. [51] Supply pressure deviations provide ample time for the hydrogen data center to react.

The downside of hydrogen-filled pipelines is leakage due to permeability and high capital investments required to construct the pipeline. [53] The expected hydrogen leakage will can incur additional 4 % transportation losses over longer distances. [53] Furthermore, this delivery method is only possible in a select few locations worldwide. In 2023, a worldwide hydrogen pipeline length was reported to be 5000 kilometers, compared to 3 million kilometers of natural gas pipelines. [54] The U.S. invested heavily in hydrogen technology, with approximately 2500 kilometers of hydrogen pipelines in operation today. [55] Overall consensus is that the hydrogen pipeline projects are successful. [55] Netherlands is following suit and is currently constructing pipeline infrastructure in industrial areas.

European Association for the Streamlining of Energy Exchange published a recommended quality specification for hydrogen in dedicated hydrogen pipelines. [56] The specification CBP 2022-001/01 recommends a minimal purity rating of 98 mol %. [56] It is likely that this purity will be used in the European pipeline network.

3.4. Purification

An essential property of hydrogen for consumers is purity. The different production methods discussed in Section 3.1 output hydrogen of different purity. Hydrogen fuel quality is particularly important in electricity production involving fuel cells, as some technologies are more sensitive to impurities. The membranes of fuel cells are particularly vulnerable to carbon poisoning, which can lead to premature failures.

On the other hand, a worse grade of hydrogen generated from industrial byproducts and methane reforming is widely available today. The industry is making efforts to standardize hydrogen purity. Hydrogen consumers in chemical industries require the absence of specific contaminants, while other applications, like internal combustion, are more lenient towards impurities. [57]

Standard ISO 14687 attempts to unify hydrogen specifications in automotive and stationary applications, and it can be found in Table 3.4. An alternative definition of hydrogen quality is in terms of grades. The grade represents the minimum "number of nines" and the minimum amount of contaminants. [57] Table 3.5 shows the breakdown of common grades.

Classification	Purity (%)	Application
A	98.00	Internal combustion engines for transport
B	99.90	Industrial fuel for power generation or heat energy source
D	99.97	PEM Vehicle Fuel cells
E-1	50.0	PEM Stationary Applications
E-3	99.9	PEM Stationary Applications

Table 3.4: Overview of ISO 14,687-2:2012 hydrogen purity standard. [57]

Grade	Purity (%)	Application
> 6.0	> 99.9999	Research grade
> 5.0	> 99.999	Ultra-high purity grade for semiconductor applications
> 4.0	> 99.99	Zero grade for fuel cell applications
> 3.5	> 99.95	Industrial grade

Table 3.5: Hydrogen grades and their application. [57]

The tables mentioned earlier are not all-inclusive representations of the fuel quality. Another consideration of the fuel is the maximum quantities of impurities in terms of parts per million (ppm). For example, hydrogen fuel for fuel cells must have the minimum amounts of the following contaminants: Carbon Monoxide < 0.2 ppm, Formic Acid < 0.2 ppm, and Formaldehyde < 0.01 ppm. [57]

The industry is moving forward with ensuring that different participants in hydrogen adoption can integrate their technologies safely. A special international technical committee, ISO/TC 197, was formed to unify hydrogen production, storage, transport, and consumption standards. [57] This is an important step the industry needs to take. This committee is currently developing 15 standards to ensure that hydrogen becomes ubiquitous energy carrier of the future. [57]

An on-site purification system could be required if the quality of delivered hydrogen is out of spec. Many purification options exist and some are commonly used to improve purity of non-sustainable production processes. [57] The most prominent technologies are outlined in Table 3.6.

Property	Palladium Membrane Diffusion	Metal Hydride Separation	Pressure Swing Adsorption
Output purity (%)	≥ 99.9999	≥ 99.9	99.999
Recovery rate (%)	> 99	90 – 95	93 – 96
Scale of use	Small to medium	Small to medium	Large

Table 3.6: Hydrogen purification technologies. [58]

3.4.1. Palladium Membrane Diffusion

Palladium membrane diffusion works on a principle of high permeability and high selectivity of hydrogen. [59] Hydrogen is physically separated by the membrane by applied partial pressure. [59] The atoms diffuse though the palladium membrane, yielding hydrogen of ultra-high quality. [59]

The advantage of this technology is that it has low energy requirements. [59] Unfortunately, the purification process requires very high temperatures around 450 °C. [59] High costs of palladium metal make large-scale systems prohibitively expensive.

3.4.2. Metal Hydride Separation

The metal hydride technique uses the process previously discussed in metal hydride storage. Impure hydrogen is pressurized into the metal hydride reactor while the impurities are discharged from the other end. [60] After the process is complete, pure hydrogen is then removed from the tank. [60] For continuous operation, it is essential to perform purification in batch mode, utilizing two or more reactors in parallel. [60] Metal hydrides can be used as storage, which is an added benefit for data center applications.

High-purity hydrogen is typically produced from 60 % hydrogen content. [60] This process can be used on gasses containing as low as 15 % hydrogen concentrations. [60] Fortunately, using hydrogen feed with a low content of impurities makes it relatively easy to achieve Grade 6 hydrogen gas. [60] One publication demonstrated successful purification of 98 % industrial hydrogen to purity level of 99.9999 %. [60] Another publication demonstrated a successful small-scale combined purification and fuel cell system rated at 200 W. [61] Furthermore, they have successfully used a metal hydride storage system for stationary applications, storing and purifying 20 Nm^3 of hydrogen in a single reactor. [61]

Unfortunately, the metal hydride purification system is difficult to scale. Operating multiple reactors to achieve continuous hydrogen output has proven challenging. [60] Metal hydrides with high hydrogen absorption capacities can use expensive metals, making large-scale installations costly, especially considering low gravimetric hydrogen density as was previously outlined in Table 3.2.

3.4.3. Pressure Swing Adsorption

Pressure swing adsorption is one of the most prevalent and widely deployed hydrogen purification technology. Currently, approximately 85 % of the hydrogen produced worldwide is purified with this method. [62] The PSA systems are used primarily in hydrogen production by SMR but are also utilized for hydrogen recovery from hydrogen-rich off-gas streams containing a wide range of impurities. [63] Hydrogen-rich gas mixture is passed though multiple stages of high-surface-area absorber to separate and remove contaminants such as CO, CO_2, CH_4, H_2O, and N_2. [62] Even though the PSA process is simple, many switching valves are needed for operation. They are vulnerable to mechanical failure, introducing reliability concerns. [63] Hydrogen PSA units typically operate at a pressure of 1.4 – 4.8 MPa and temperature of 38 – 66 °C. [63]

3.5. Electricity Generation

Fuel cells are technologies that produce electricity through hydrogen and oxygen electrochemical reactions. [64] All fuel cells are made from three components: anode, cathode, and electrolyte. On the anode side, hydrogen is oxidized, releasing electrons and protons. [64] The electrons travel through the resistive load to the cathode, producing an electric current. [64] The protons pass through the electrolyte to the cathode, which reacts with oxygen and the electrons to form water. [64]

This technology has many advantages over fossil energy generation methods, including modularity, high efficiency, reliability, long lifespan, and CO_2-free operation. [64] The absence of moving parts makes fuel cells particularly suitable for data center deployments, as fewer points of failures improve operational reliability.

Figure 3.2 provides an overview of a typical fuel cell setup, including supporting components required for operation. Fuel cells could use hydrogen, natural gas, or methane as fuel. Since this feasibility study focuses on sustainability, only fuel cells that use hydrogen will be considered. The following fuel cells have been identified as suitable: low/high-temperature proton exchange membrane (LT-PEMFC/HT-PEMFC) and alkaline (AFC). [65, 64] Table 3.7 outlines these technologies in terms of their common properties. Other technologies, such as Solid Oxide, Molten Carbonate, Phosphoric Acid, and Direct Methanol, are unsuitable for hydrogen-only operation. [64]

Operation temperature is the most important consideration, as waste heat must be reused in the cooling solution for high efficiency. The coupled system must operate within a slight temperature difference to

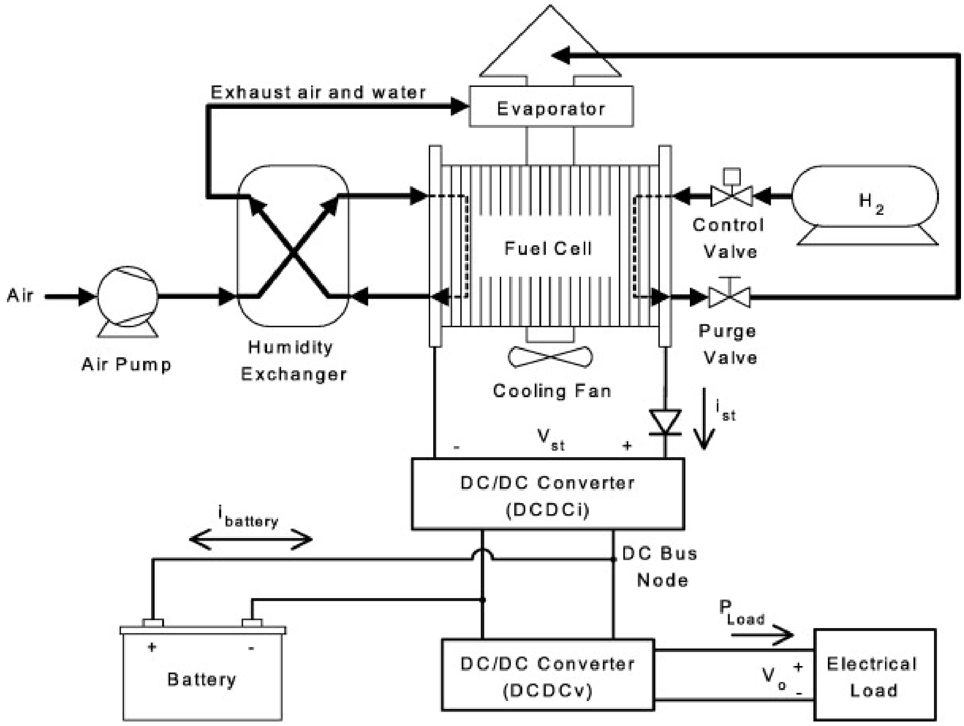


Figure 3.2: Fuel cell diagram. [66]

	LT-PEMFC	HT-PEMFC	AFC
Operation Temperature (°C)	50 – 80	160 – 200 [67]	60 – 90
Minimal H_2 Purity (%)	99.99	75 [68]	99.99
Electrical Efficiency (%)	45 – 60	30 – 40 [67]	40 – 60
Power Density (mW/cm^2)	350	-	100 – 200
Operational lifetime (hr)	40 000	17 000 [69]	10 000
Source	[70, 64]		[70, 64]

Table 3.7: Overview of hydrogen fuel cell technologies.

be compatible. In general, higher operational temperatures enable better reuse of waste heat and allow district water preheating. Research suggests that the waste heat of fuel cells can also be an exclusive source of energy for cooling, albeit with lower overall efficiencies. [71]

The second factor is hydrogen purity requirements. Some fuel cells require pure hydrogen and are highly sensitive to CO_2 impurities. [72] High purity requirements can drive up costs and require installing an on-site purification system. Lax hydrogen purity requirements of the fuel cell allow low-grade, cost-effective hydrogen sources to be utilized.

Lastly, operational lifetime is an important consideration. Fuel cells need to be replaced preemptively during regular operation. They slowly deteriorate and must be replaced. Better lifespans will significantly decrease operational costs and enable higher reliability tier certifications.

3.5.1. LT-PEMFC

Low-temperature proton exchange membrane fuel cells are typically referred to as PEMFC in the literature. Thanks to their widespread use inside hydrogen vehicles, they are the most mature fuel cell technology on the market. [72] Their research began for space and submarine applications in the 1950s, giving this technology a head start. [72] They have been used commercially for decades, with the current durability of over 5600 hours of continued operation. [65] Furthermore, operating within desirable temperature and humidity conditions can further increase their lifespans, with some research suggesting that 16 000 hours of continuous operation is possible. [65] Several projects have successfully reached the megawatt scale with this technology. [72] This technology's popularity and battle-tested nature make it an appealing choice for risk-averse data center applications.

Other advantages of this chemistry include fast startup times and high energy density. The fuel cells can quickly ramp up electricity production to meet power demands. The energy density allows for relatively compact systems, which is advantageous in space-constrained environments like data centers. [70]

The negatives include using expensive catalyst materials, although prices are dropping due to economies of scale. Furthermore, LT-PEMFCs are sensitive to carbon fuel impurities, as was discussed in Section 3.4.

3.5.2. HT-PEMFC

High-temperature proton exchange membrane fuel cells are a newer development than low-temperature PEM fuel cells. They offer several advantages, such as insensitivity to fuel impurities and higher operational temperatures, which enable higher overall efficiencies and produce higher quality waste heat for cooling applications. [73] However, HT-PEMFCs have some drawbacks, including lower lifespans than LT-PEMFCs and more complex internal heat transfer systems due to their higher operating temperatures. [69] Additionally, achieving the megawatt scale with HT-PEMFCs has proven challenging, partly due to the increased thermal management requirements and accelerated material degradation at high temperatures. [73, 69] The startup performance of HT-PEMFCs is also slower than that of LT-PEMFCs. [73]

3.5.3. AFC

Alkaline fuel cells are one of the earliest technologies, with strong commercial development in the 1970s. [72] AFC has the advantage of fast startup, quick response time, and high efficiency. [64] However, their disadvantages stifled global adoption. Low energy density limits the power to about 20kW per fuel cell stack, making a one-megawatt target unreachable. [64] AFC is very sensitive to carbon dioxide, requiring total elimination of CO_2, even from the outside air. [64]

3.6. Cooling

Traditional data centers use vapor-compression refrigeration systems for cooling because they are electrically efficient. [27] However, generating cooling without electricity is essential to achieve a hydrogen-only data center goal. The absorption refrigeration cooling system (ARS) offers a promising alternative to the conventional vapor-compression systems, utilizing heat from low-grade energy sources for cooling. [74] If waste heat is insufficient to accommodate the cooling load, direct firing with hydrogen is possible. ARS systems of various stages and working fluids are available on the market.

Table 3.8 outlines various configurations and their performance. The system's efficiency is measured by the Coefficient of Performance (COP), a ratio of cooling capacity at the evaporator in relation to heat input for the generator. [75] Higher COP means more cooling energy is produced than consumed by the ARS.

System	Generator Temperature (°C)	Working fluid	COP
Single Effect	80 – 110	LiBr/Water	0.5 – 0.7
Single Effect	120 – 150	NH_3/Water	0.5
Double Effect	120 – 150	LiBr/Water	0.8 – 1.2
Triple Effect	200 – 300	LiBr/Water	1.4 – 1.5

Table 3.8: Overview of absorption technologies. [75]

Choosing the appropriate working fluid is essential when selecting an absorption system. Hundreds of configurations exist in the literature, yet only a few are used commercially today. [75] Only mature solutions will be considered to maximize reliability. Furthermore, the configuration must be highly efficient and have low purchasing costs. According to findings in Section 3.5, it is necessary to ensure that the waste heat produced by the fuel cell is compatible with the specification of the generator. A lithium bromide water mixture is preferred as a working fluid as it operates at a lower temperature than ammonia-based systems.

Absorption refrigeration systems are a good choice for the hydrogen data center. Heat, which would be otherwise lost to the surroundings, can reduce fuel usage and, therefore, CO_2 emissions. [75] In the case of a large-scale hydrogen fuel cell stack, the infrastructure's operating costs can decrease dramatically.

Another advantage of the ARS in data center applications is high reliability due to few mechanical components. A single pump is required in single-effect, and two pumps are used in double-effect systems. [74] Compared to the vapor-refrigeration, the pumps used in the absorption cycle use little electrical power. [74]

3.6.1. Single Effect ARS

A single-effect absorption refrigeration system will be used to explain operational principles. As shown in Figure 3.3, the absorption cooling system consists of four main components: the generator, condenser, evaporator, and absorber. Heat supplied to the generator raises a weak coolant and pushes it to the condenser, which cools it down to a liquid. Once the coolant reaches the evaporator, the refrigeration vaporizes to absorb heat. Next, the weak solution in the absorber absorbs the vapor, and the diluted solution is pumped into the generator to release the refrigerant vapor. This cycle continues in repetition. [74] Temperature difference between the generator and the evaporator drives the cycle.

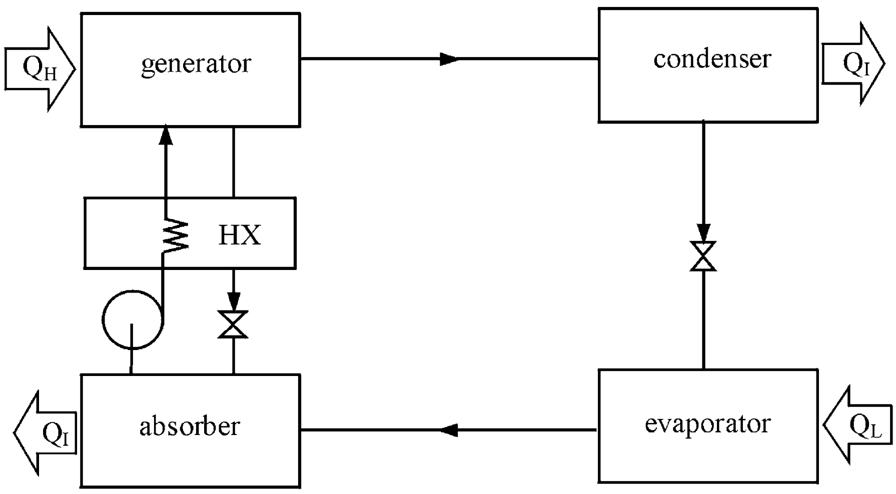


Figure 3.3: Schematic of a single-effect absorption refrigeration cycle. [75]

Single-effect ARS with lithium bromide fluid is a good candidate. It can operate at low temperatures that align with the operating temperature of LT-PEM and AFC fuel cells. Single-effect ARS systems are commonplace in the industry and are cheap to manufacture and maintain. Unfortunately, a low coefficient of performance could be an issue. The data center room cooling load is the same as the electrical load, and chiller efficiency below 1 provides insufficient cooling.

The solution to overcome low performance is integrating a hydrogen burner into the generator (Q_H in Figure 3.3) to boost heat flow. Hydrogen's high energy density makes it a great fuel for the co-generation strategy. [71] It is common for commercial systems to offer direct firing mode. The low-grade waste heat is amplified by burning energy-dense fuels inside the generator. Usually, non-sustainable fuels such as natural gas are used for this purpose. According to research from the University of Malaya, a hydrogen-based absorption refrigeration system running on optimum hydrogen conditions used 29 % less electricity than a comparable propane system. [76].

3.6.2. Double Effect ARS

The multi-effect absorption refrigeration cycles are used to increase system performance when high-temperature heat source is available. [75] Double or triple-effect systems essentially stack one absorption cycle on top of another, as shown in Figure 3.4 for a double-effect system. [75] The refrigeration cycle is configured so that the heat rejected from high-temperature generator is reused in low-temperature generators. [75] This process increases performance while increasing temperature requirements. [75] Manufacturing and maintenance costs increase significantly with every added stage. Triple-effect absorption systems are not used in practice due to diminishing performance compared to system complexity. [74]

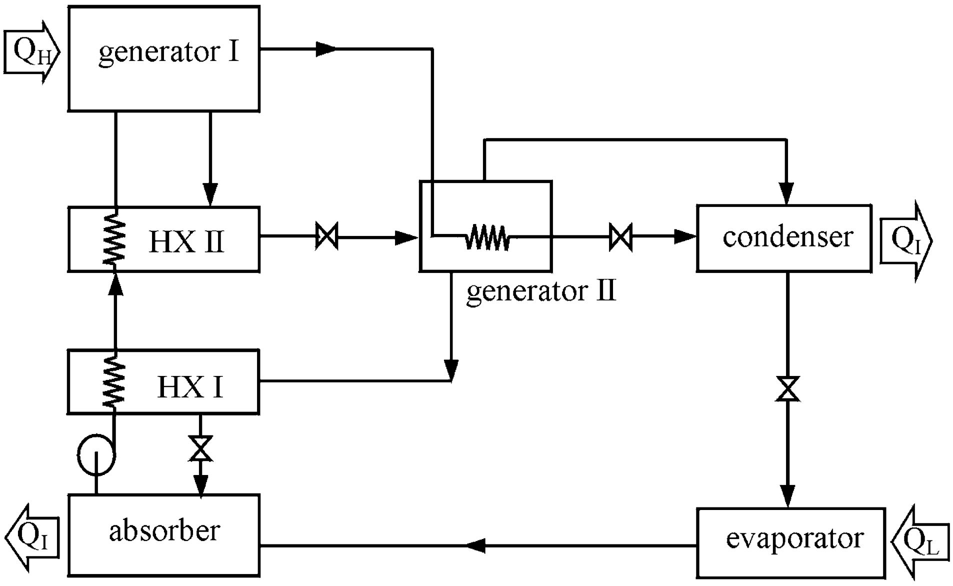


Figure 3.4: Schematic of a double-effect absorption refrigeration cycle. [75]

4

Hydrogen Data Center Design

This chapter will propose the designs of a hydrogen data center. Due to various circumstances, the overall reliability rating is limited to tier II. Conforming precisely to the reliability specifications is challenging due to the presence of hydrogen and waste heat systems in the design. Traditional data centers only consider electrical and mechanical systems for reliability certification. The reliability of hydrogen and waste heat distribution paths will be carefully considered while applying performance standards analogously to the tier definitions by the Uptime Institute. [5]

The feasibility study of a fully hydrogen data center will primarily consider tier II design. Lower reliability deployment is a good starting point for exploring the hydrogen infrastructure. It is theoretically possible to achieve tier IV design, albeit with various limitations regarding compliance with formal tier IV performance requirements.

Compatibility between various hydrogen technologies reviewed in Chapter 3 presents an opportunity to build two different design configurations. Low-temperature and high-temperature designs will be proposed.

4.1. Module Design

A modular approach to the design was proposed. A single data center module is confined within two adjacent rooms: a server room for the IT equipment and a mechanical room for the electrical and cooling systems. Cooling components are located on the roof. A top-down diagram is available in Figure 4.1. Each module is self-contained and responsible for providing the servers with 1 megawatt of electrical power and cooling. Close physical proximity between the two rooms is essential to minimize the length of routed resources such as power and cooling fluids.

The room on the right is dedicated to housing the servers. The room is arranged in the industry-standard cold-isle hot-isle configuration to isolate the cold intake and hot exhaust thermal zones. The hot air is output between the servers on the hot isle above the floor. This hot air is fed into the CRAH unit, where heat is removed via its evaporator. The cooled air is then moved underneath the servers to the cold isles. Cold air is fed through the perforated floor and ready for intake by pressure from the server fans. This cycle is repeated continuously, with various sensors monitoring operations.

A separate room on the left houses the fuel cell stack, ARS, UPS, and other supporting equipment. Fuel cells and ARS are manufactured as a single unit, minimizing efficiency losses. Traditionally, the two systems are coupled rigidly, and electrical output directly influences cooling power. This behavior is undesirable and can negatively infuence the thermal environment of the server room. The proposed design in Figure 4.2 adds ARS hydrogen-fired operation mode, fuel cell radiator, and district heating to partly decouple electrical and thermal systems.

Data centers with higher computing capacities can be built by adding more modules. This design philosophy is great for rapid research & development. It is also convenient from the construction point

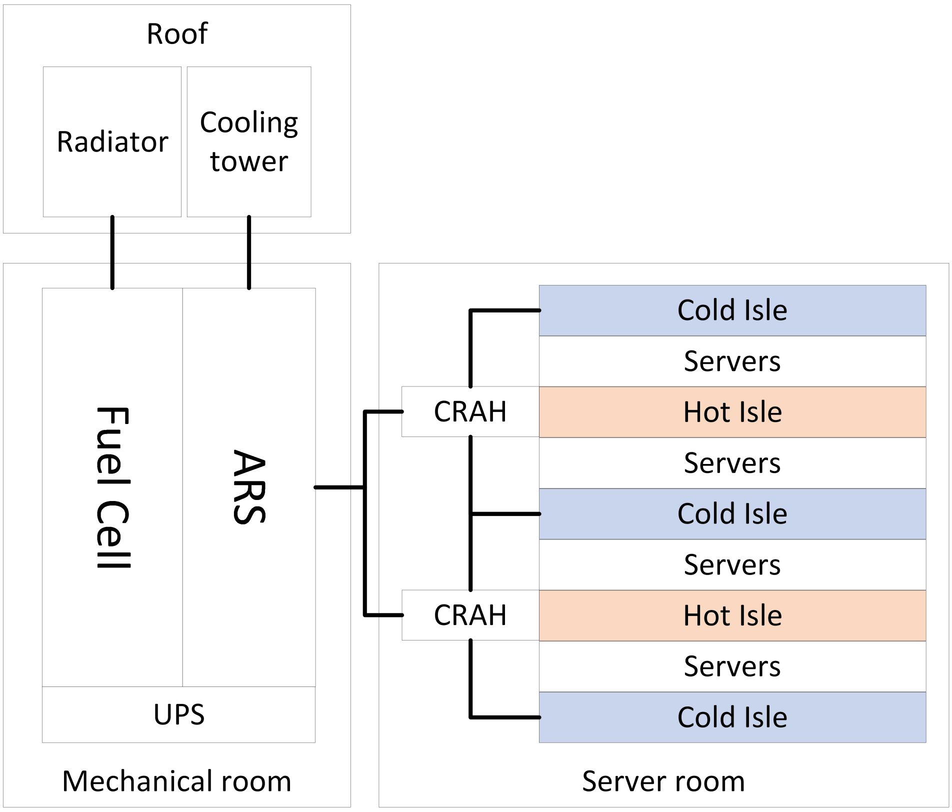


Figure 4.1: Layout of a hydrogen data center module, top view.

of view and cost-effective in practice. A single well-tested design can be installed at various locations, standardizing green hydrogen adoption in new data centers worldwide.

Modular design is partly inspired by a trend in hydrogen technology solutions. Many companies build and sell hydrogen infrastructure inside standardized shipping containers. The containerized products simplify installation, modularize whole systems, and increase deployment speed. Another reason for the proposed design is the limitation of fuel cell systems. The physics of fuel cell technology imposes constraints on the maximum power of the stack. As of today, the maximum power achieved by a commercial fuel cell system is 1.2 MW. [77] Meanwhile, an absorption refrigeration system can support much higher cooling loads. The unnecessary complexity of linking multiple fuel cells to a single ARS is avoided by consolidating power and cooling into a standalone module.

This design is tier II, as it fulfills the following requirements and performance confirmation tests as per the specification [5]:

- Redundant capacity components can be maintained without shutting down any computer equipment.
- A single non-redundant distribution path serving the computer equipment requires shutdown during maintenance.
- Unplanned outage will impact the computer equipment.

4.2. Cogeneration

Cooling systems that enable higher efficiencies by waste heat reuse are classified as cogeneration technologies. With heat recovery or heat reuse, the energy footprint of the data center can be reduced. A topic of these two ways to maximize operational efficiencies will be explored.

The heat recovery process is upgrading low-quality heat into usable energy with the help of heat exchanger devices such as heat recovery steam generators, water heaters, or air heaters. [78] The arrangement of these heat exchangers aims to extract the waste heat and use it for heating other systems. This process can significantly increase the efficiency of industrial systems requiring high operational temperatures. [78] In data center applications, district heating is a common way to extract these benefits. [79]

District heating is economically viable and ecologically beneficial. [79] Heat pumps are used to upgrade the low-grade heat before pre-heating a city's water supply. [79] This implementation poses multiple advantages: the city provides financial incentives for the heating, and the data center can reduce water use, as the cooling towers use less water to dissipate heat. This method of boosting efficiency has been used successfully in current data center deployments. [79] When implementing district heating, some critical considerations are fluid temperature, distance to the district infrastructure, and data center power capacity. [80] The data center heat output must be high enough to have a sizable economic effect. [80]

The second way to boost efficiency is through heat reuse, where waste heat is redirected into another system inside the data center that requires heat for operation. These highly integrated systems are typically custom-built to accommodate a particular load. In the case of the proposed design, waste heat is directed to the generator of the absorption refrigeration chiller, which drives the cooling cycle.[78] The umbrella term for these systems is combined cooling, heat and power (CCHP). [78] In some literature, they are called trigeneration systems because they simultaneously fulfill these three tasks.

Fuel cells and absorption refrigeration are a perfect match for CCHP applications. [78] Table 4.1 is a compatibility matrix between the fuel cell types and absorption refrigeration system configurations. The symbols "+" and "-" are used to indicate the suitability or incompatibility of each combination. For example, the heat output of an LT-PEM fuel cell at 60 – 80 °C is suitable for operation in a single-effect absorption refrigeration cycle operating at 80 – 100 °C. According to research, this combination achieves an overall efficiency of around 60 – 80 %. [81, 78] Figure 4.2 demonstrates the flow of heat inside the proposed cogeneration system.

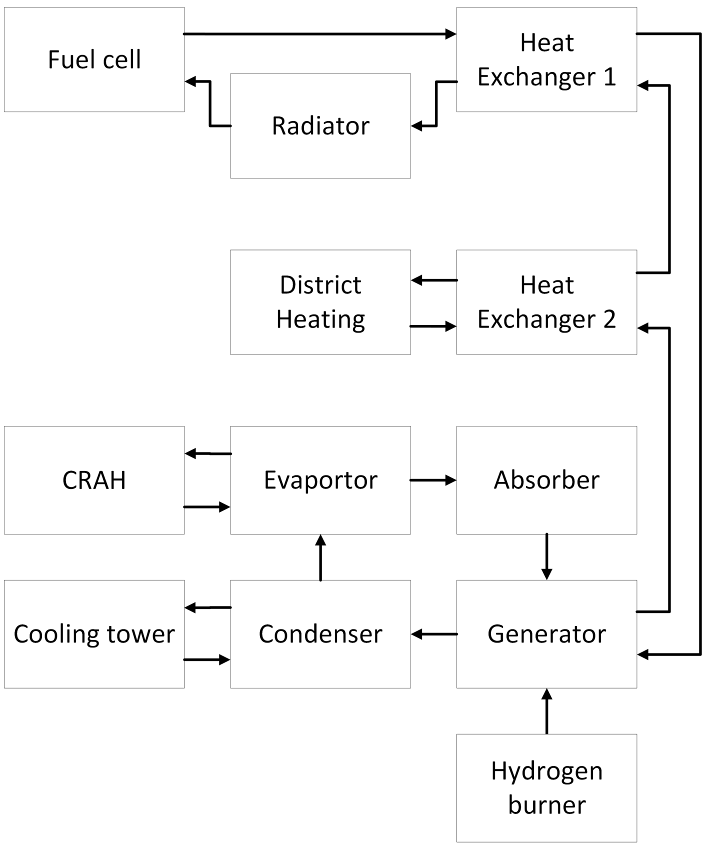


Figure 4.2: Heat flow diagram of fuel cell with direct-fired hydrogen absorption refrigeration system. [78]

In the proposed system, the waste heat from the fuel cell is transferred to the generator of the ARS via heat exchanger 1, and then the thermal flow rate is boosted by the hydrogen burner. The thermal fluid can then be directed to heat exchanger 2 to provide district heating. The cycle completes at the heat exchanger 1. A radiator within the fuel cell loop is used to cool down the fuel cell if the hydrogen burner introduces excessive thermal energy while the district heating does not cool down enough. The hydrogen burner and fuel cell radiator enable the thermal decoupling between the ARS and fuel cell.

However, decoupling electricity generation from the cooling power can be challenging. The module's control system should use sensors, valves, and heat exchangers to adjust refrigeration power independently of the IT load. The heat generated by the IT equipment is linearly correlated with power consumption, but the changes are not instantaneous. The change in thermal output of the servers needs to propagate through the air in the server room, then travel through the cooling loop of the CRAH and ARS before it can be adjusted. The goal of the control system is to proactively regulate the thermal state of the entire loop in Figure 4.2 to offset the transient differences between power generation, waste heat temperature, and computer room temperature.

Fuel cell / ARS	LT-PEM	HT-PEM	AFC
Single-effect	+	-	+
Double-effect	-	+	-
Triple-effect	-	+	-

Table 4.1: Compatibility matrix for operational temperatures between fuel cell and ARS.

The proposed cogeneration system has been tested physically. For example, Panasonic Corporation has built a prototype and has demonstrated it by providing power and cooling to a fuel cell factory. [82] The system operated at 570 kW and demonstrated an impressive 95 % energy efficiency. [82] Their implementation works at 70 °C, an improvement of 10 °C compared to other designs on the market. [82]

4.3. Component Selection

The next step in prototyping a fully hydrogen-powered data center is component selection. The primary objective is to fulfill previously outlined operational requirements while adhering to the sustainability goals.

Firstly, the appropriate hydrogen supply method must be determined before selecting internal components. The quantity of hydrogen required to generate more than one megawatt of power is quite substantial. Therefore, a hydrogen pipeline is most suitable for this application. As detailed in Section 3.3, truck delivery is not appropriate logistically and economically. Furthermore, issues concerning the consistency and purity of pipeline hydrogen gas will be addressed.

Secondly, for storage, a strategic choice is to utilize a dual hydrogen supply scheme involving gaseous high-pressure backup tanks alongside the pipeline to ensure system reliability and minimize downtime in the event of pipeline pressure fluctuations or failures. Installing industrial-scale UPS is essential to support the fuel cells during cold start and react to IT demand changes. The on-premise hydrogen backup should be sufficient to support peak load for approximately two days, increasing operational availability.

Thirdly, proton exchange membrane fuel cells are selected to generate electrical energy from hydrogen. Wide industry adoption and high demand for this technology are the driving factors for the chemistry selection. As the most mature fuel cell technology available, manufacturers are interested in producing large-scale fuel cell stacks. PEM fuel cells have the highest potential for cost reduction in the future, enabling the next generation of clean and economical data centers. [83] Both low-temperature and high-temperature variants will be considered.

Finally, an absorption refrigeration chiller will be used for cooling. Reusing the heat generated by the fuel cells is very advantageous efficiency-wise despite the lower coefficient of performance compared to traditional refrigeration technologies. Small energy use for cooling in the proposed cogeneration system is expected.

4.3.1. Pipeline Delivery

The Netherlands plans to deploy a hydrogen pipeline in the industrial area of the country, greatly simplifying the logistics of hydrogen delivery. Building a sustainable data center in that area provides a unique opportunity for experimental deployment today. The 2030 goal is to build 1200 kilometers of the pipeline, spanning the entirety of the Netherlands and connecting to Germany and Belgium. [84] By 2040, it is proposed that 28 European countries can be linked together with over 53 000 kilometers of pipeline, bringing even more benefit to consumers and producers. [84] Taking advantage of this opportunity is crucial, as demand for the pipeline is expected to increase. The first 30 kilometers are planned to be opened by 2025, and they are located in Pernis, an industrial municipality. [84] Figure 4.3 provides a map of the proposed pipeline in the Netherlands by 2030.

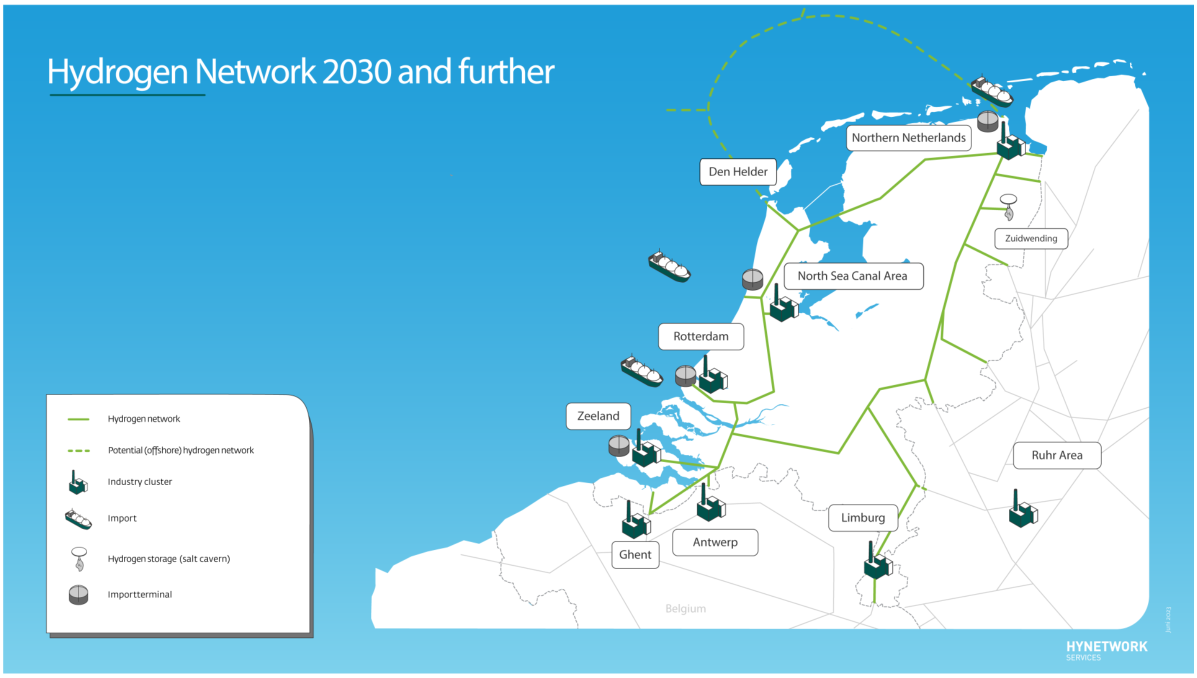


Figure 4.3: Map of proposed hydrogen pipeline. [85]

Hydrogen pipelines have had successful deployments. A small-scale 12-kilometer pipeline in the Dutch province of Zeeland has operated reliably for three years. [86] The United States has been ahead of other countries regarding hydrogen distribution networks. [21] States of Texas and Louisiana trade hydrogen with a pipeline spanning a total of 600 miles. [87]

Delivering hydrogen via trucks is not viable due to the sheer volume involved. For instance, in a pilot project, Microsoft tested using compressed gaseous hydrogen to power a 250 kW load for 48 hours, which consumed 100 000 kilograms of hydrogen. [20] Even though the goal was to test hydrogen as a backup to traditional diesel generators, it is clear that regularly delivering hundreds of tonnes a day is not logistically feasible with gaseous hydrogen truck delivery. According to Table 3.3, the pipeline becomes the only feasible option, as it can carry up to 100 tons of hydrogen per hour, compared to the throughput of 400 kilogram for a single truck.

The only disadvantage of using the hydrogen pipeline delivery method is the lack of redundancy. One distribution path of hydrogen hurts reliability, as a single point of failure results in a data center shutdown, which is against the reliable design principles. Only one pipeline will be available, as building multiple in the same location does not make economic sense. Therefore, this strategy will limit the maximum reliability certification to tier III. The workaround is to utilize a secondary supply source when the pipeline fails. Hydrogen can be delivered on demand by a source that operates independently. With sufficient stored hydrogen on-site and enough for 48 hours of operation, the data center operator has enough time to arrange a large-scale delivery of new backup storage. Empty tanks are replaced with filled ones while the pipeline is not operational. If lower reliability is acceptable, on-site storage can be omitted or scaled down in size.

Information regarding the planned specifications of the Netherlands pipeline is compiled from various sources and is summarized in Table 4.2. These specifications are sufficient for stable operation, as the pipeline is designed to support large consumers. The guaranteed hydrogen purity is concerning, as some fuel cell technologies cannot operate on this hydrogen directly.

Property	**Value**
Hydrogen purity (% mol/mol)	98 – 99.5
Gas temperature (°C)	5 – 30

Table 4.2: Hydrogen pipeline specification. [88, 89]

4.3.2. Proton Exchange Membrane Fuel Cell

Proton exchange membrane fuel cell technology has been chosen to generate electricity inside the hydrogen data center due to its technological maturity and high manufacturing capacity. [90] Figure 4.4 demonstrates the difference between real-world installation capacities of different technologies, and PEM chemistry is a definite leader.

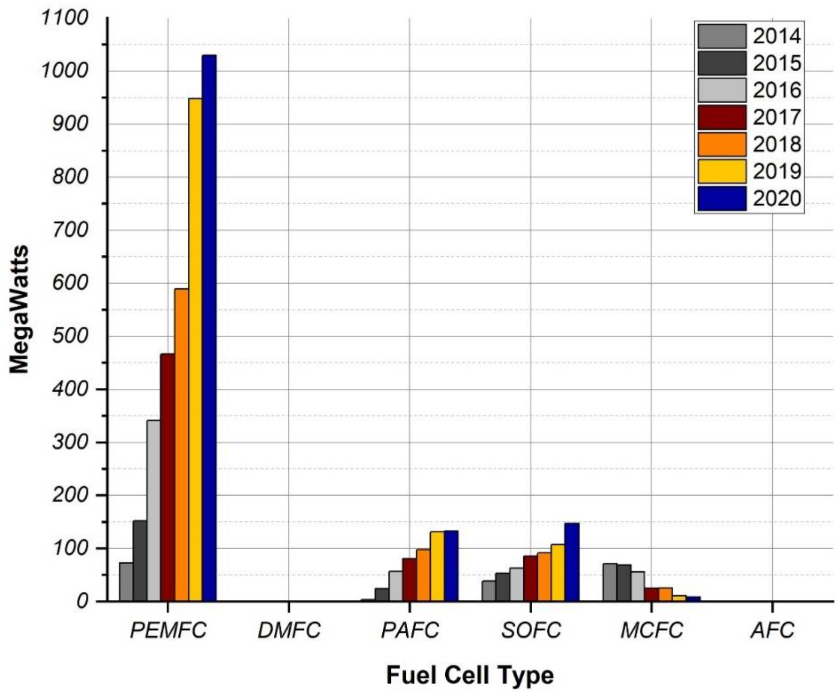


Figure 4.4: Fuel cell installation capacities. [90]

The low-temperature and high-temperature PEM fuel cells operate at a reasonable temperature and have fast start-up times according to Table 3.7. Their operation temperatures are sufficient to be used inside the ARS cooling system. Alkaline fuel cells also meet the temperature and start-up requirements, but they are a bad choice because they have low market share, low power density, and short operational lifespan.

Market research was performed to find commercially available large-scale stationary PEM fuel cells. Table 4.3 summarizes some of the available options. At the megawatt scale, only low-temperature variants are available. Unfortunately, they require high-purity hydrogen, necessitating an on-cite purification system. Stationary fuel cell systems exhibit long lifetimes, benefiting the maintenance procedures. Some manufacturers express operational lifetime as the total lifespan of the system and not of individual fuel cells. It is safe to assume that regular maintenance must be performed at intervals similar to other manufacturers, about every 25 000 – 30 000 hours.

	Accelera Stationary Power	Ballard FCwave	PlugPower GenSure Mw-Scale Power	Nedstack PemGen CHP-FCPS-600
Capacity (kW)	800	200 – 1200	1000	600
Operating temperature (°C)	-	65	-	65
Hydrogen purity (%)	-	-	99.95	99.95
Fuel consumption (kgH_2/MWh)	56 – 70	-	66 – 69	66
Operational lifetime	> 20 years	25 000 hr	> 20 years	30 000 hr
Source	[91]	[77]	[92]	[93]

Table 4.3: Commercially available high-power stationary LT-PEM fuel cells.

Table 4.4 outlines available experimental and research high temperature fuel cells. The technology has not reached mass production scale, but it is a promising development which should be considered in the future. As for the high-temperature design, difficulties regarding the on-site purification system make high-temperature fuel cells an attractive option.

	Advent HT-PEM MEA	Blue World Blue S18
Capacity (kW)	100	18
Operating temperature (°C)	160 – 180	120 – 180
Hydrogen purity (%)	80.4	-
Operational lifetime (hr)	> 18 000	-
Technology readiness level	Pre-production	Low volume production
Source	[94, 95]	[96]

Table 4.4: Upcoming HT-PEM fuel cell technologies.

After reviewing options available on the market, the Ballard FCwave fuel cell system stood out. Their stationary application fuel cells are an excellent fit for the scale of the project. Ballard's technology is tillable — altering the amount of fuel cell modules can achieve an overall output power between 200 and 1200 kW. [97] Only 5.5 square meters of floor space is required at the maximum configuration. [97]. This fuel cell system integrates super-capacitors, allowing operation with autonomy and greater reliability. [97]

4.3.3. Pressure Swing Adsorption

A purification system is required when utilizing LT-PEM fuel cells for power generation. As the pipeline will be used as the primary means of hydrogen transport, the minimum guaranteed purity of 98 % must be upgraded to a quality of 99.99 % or higher to ensure compatibility with LT-PEM fuel cells. The high-temperature design does not require purification.

Any of the suitable technologies outlined in Section 3.4 can be used for data center applications. Pressure swing adsorption is the most promising technology as it is widely used and can operate on a large scale. Even though there are concerns about mechanical reliability, PSA is the most cost-effective option for purifying large volumes of hydrogen required for data center operation. [63] It outputs a continuous steam of hydrogen gas free of the contaminants poisonous to the LT-PEM fuel cells.

Other technologies, such as metal hydride and palladium membrane diffusion, have only been demonstrated on small or pilot scales. [58] These technologies are continuously improving in costs and manufacturing volumes and may eventually become a better fit for a hydrogen data center.

4.3.4. High Pressure Tank Storage

On-site storage of hydrogen must be considered for high-reliability deployments. If lower reliability is acceptable, the storage can be omitted. From the technologies discussed in Section 3.2, high-pressure gaseous cylinders are the best option. Low prices of storage containers and relatively high volumetric and gravimetric energy densities make compressed hydrogen a suitable option for backup purposes. Pressurized hydrogen tanks should be run in parallel with the pipeline supply and activated during malfunctions. With sufficient storage for 24 – 48 hours of operation, the data center staff has enough time to arrange a large-scale truck delivery of new backup storage. Empty tanks can be replaced with filled ones seamlessly without interrupting the operation.

4.3.5. Direct-Fired Absorption Refrigeration System

A direct-fired absorption refrigeration system is chosen to capitalize on the waste heat of the fuel cells. An integrated hydrogen burner is used to enhance cooling performance without significant electricity use. Direct-firing is the key to fulfill hydrogen-only criteria of the design. Table 4.5 outlines commercially available absorption refrigeration systems of single and double effect configurations.

	Thermax S2 D4	**TecoChill CH-300x**	**Yazaki CH-MG200**	**York YHAU-CL/CH**
Type	Double-effect	Double-effect	Double-effect	Single-effect
Capacity (kW)	1069	1055	703	105 – 7034
COP	1.5	1.5	-	-
Operation temperature (°C)	75 – 250	-	-	70 – 160
Direct-fired fuel	Natural Gas, Diesel	Natural gas	Natural gas	No
Supports waste heat reuse?	Yes	Yes	No	Yes
Source	[98]	[99]	[100]	[101]

Table 4.5: Commercially available absorption refrigeration systems.

Unfortunately, commercially available ARS are not available with hydrogen direct-fired mode. A few publicly known prototypes are in the validation stage of development. Ebara Corporation have lanuched a pilot test of a hydrogen-powered absorption chiller-heater code named Model RHDH. [102] This combined heating and cooling system utilized high-quality hydrogen as only fuel source. [102] The company aims to achieve carbon neutrality by 2050 with more testing and deployments of such systems. [102].

4.4. Infrastructure Design

An infrastructure block diagram of a tier II hydrogen data center can be found in Figure 4.5. The design is much simpler than the traditional data center in Figure 2.4.

The fuel cell and ARS are supplied with hydrogen fuel from two sources. During regular operation, the hydrogen from the pipeline is used exclusively. Backup gaseous storage provides fuel during pipeline malfunction, and the hydrogen switch automatically fails over.

Hydrogen purification is required when the fuel cells require high purity, which the pipeline does not satisfy. The purification system should be omitted otherwise.

The power conditional system has lots of improvements over the traditional design. Direct current bus is used throughout the electrical systems. DC electronics are generally simpler, resulting in cheaper components that operate at higher electrical efficiencies than their AC counterparts. Ideally, the DC bus should use a standard voltage rating for which the servers are designed. These standards differ by country; therefore, the European data center will use a standard voltage of 240 V. Fuel cell power output is connected to a DC/DC converter to regulate the voltage output. The voltage can change due to fluctuation in combined server power and during startup from a cold state. The utility grid connection and AC/DC converter are used only during black-start procedures. The grid bootstraps the UPS, fuel cell, and cooling system; the control system computers and components such as pumps need the fuel cell's power to work. The UPS must be tightly integrated with the fuel cells. Its role is to absorb power spikes and monitor the electrical system. The USP must be ready to absorb voltage and amperage fluctuations related to IT load or component failures. The ARS depends on hydrogen

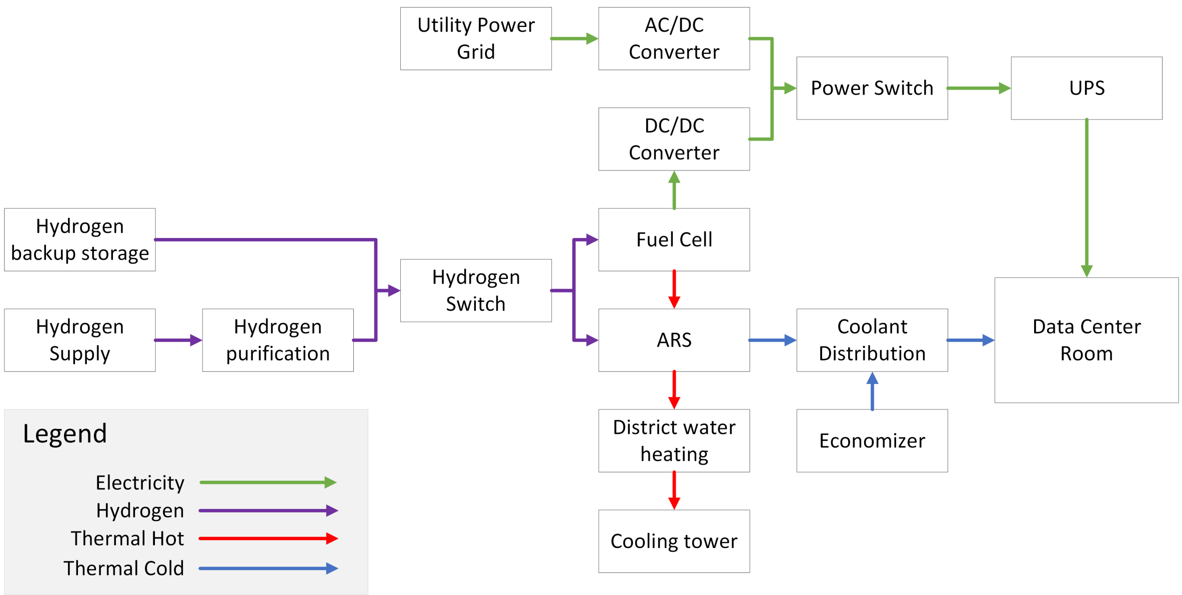


Figure 4.5: Infrastructure component diagram of a proposed hydrogen data center.

fuel for direct-firing operation and waste heat of the fuel cell. The evaporator is connected into the cooling distribution system, which routes chilled fluids to the CRAH units inside the data center room. Additional components such as an economizer and district water heating can increase efficiency further and create extra revenue streams. A cooling tower is a vital component that consumes water to drive the thermodynamic cycle. Water usage is reduced or eliminated if water byproducts of the fuel cell operation are routed to the cooling tower. A hydrogen design presents many opportunities for internal recycling of resources.

Given the chosen hydrogen technologies in Section 4.3 and cogeneration concepts described in Section 4.2, Table 4.6 outlines chosen components for each design.

	Low temperature	**High temperature**
Supply	Pipeline	Pipeline
Electricity Generation	LT-PEM fuel cell	HT-PEM fuel cell
Purification System	Pressure swing adsorption	-
Storage	Gaseous tank	Gaseous tank
Cooling	Single-effect ARS	Double-effect ARS

Table 4.6: Components selection of the two proposed designs.

4.5. Operational Procedures

An operation procedure for potential failure events must be established before the operation of the data center begins. Planning for failure is essential to decrease the downtime when the failure occurs eventually. These procedures should be implemented on the control system level, as minimization of human-driven actions dramatically reduces the chances of operational error. Procedures related to black starts, hydrogen supply issues, fuel cell failures, and ARS failures will be outlined.

4.5.1. Black Start

The black start procedure is initiated when the data center is powered on. Complete shut-off could have been caused by failure or regular maintenance. The worst-case scenario will be considered: the fuel cell and ARS are cold, and the UPS has no charge. The startup procedure is the following:

1. Connect the power switch to the utility grid.

2. Charge UPS to a minimal power level.
3. Start a small portion of the servers.
4. Activate pumps and fans of the fuel stack and the ARS and wait for nominal operation.
5. Start the fuel cell and activate the hydrogen burner inside the ARS.
6. Slowly start the servers as the fuel cell increases power output and ARS produces sufficient cooling.
7. When FC and ARS are warm, and UPS is charged sufficiently, disconnect the utility grid.
8. Wait until all servers are running.

4.5.2. Pipeline Supply Issue

The hydrogen supply malfunction procedure is activated when issues with the primary fuel supply are detected. The malfunction could be in the pipeline or the purification system. If the incoming pressure to the hydrogen switch is below a certain threshold, start the following procedure:

1. Switch hydrogen supply from pipeline to backup storage.
2. Determine failure severity. If a prolonged supply outage is expected, order delivery of replacement backup hydrogen.
3. Replace empty backup tanks with full ones during prolonged outages.
4. When the pipeline supply has sufficient pressure, disconnect backup storage from the switch.

A secondary gaseous pressurized hydrogen supply source is critical in ensuring that fluctuations or malfunctions in the hydrogen supply do not affect the IT equipment. Hydrogen storage should be able to supply the data center autonomously for 24 hours. This time-frame should be sufficient for the pipeline to perform repairs. With sufficient buffer of backup fuel, prolonged failures can be continuously supported by gaseous hydrogen delivery. As discussed previously in Section 3.3, this mode of hydrogen transport is not economical, but it is necessary to avoid lengthy downtime.

4.5.3. Fuel Cell Failure

Maintenance of a single fuel cell stack is a routine procedure addressed by N+1 configuration. The fuel cells must be maintained approximately every 30 000 hours, and the system should be designed with concurrent stack replacement in mind. It should be possible to disconnect a single fuel cell stack without load and replace it with the new one while the rest of the stacks output power. The UPS is responsible for regulating drops in power when the fuel cell stack fails unexpectedly. Load balancing between the fuel cell stacks is essential to ensure that two cells never require maintenance simultaneously.

If more fuel cells fail than the configuration can support, a strategic shutdown of some servers is performed instead of a complete shutdown. If the whole fuel cell system malfunctions, the IT equipment will experience downtime.

4.5.4. ARS Failure

Malfunction or maintenance of the ARS is the worst-case scenario. Since no redundancies exist, the IT equipment will experience downtime. Class A continuous cooling is impossible due to a single point of failure.

4.6. Safety Considerations

Handling high-purity hydrogen fuels requires extra caution due to the high energy density of the gas. Hydrogen is flammable in air in concentrations ranging from 4 % to 75 % by volume. [103] Hydrogen has a low ignition energy of 0.02 mJ. A tiny electric spark is enough to cause an explosion. In comparison, natural gas and gasoline require significantly higher ignition energies of about 0.3 mJ. [103] Therefore, adopting rigorous safety measures to mitigate the risk of accidents is essential.

Another safety concern when working with hydrogen is its high permeability. [103] Hydrogen is the smallest possible molecule that permeates through solid materials. The permeation happens through the concept of diffusion. H_2 is split into separate atoms that physically move inside the material, eventually saturating it and leaving the containment on the other side. The leakage rate depends on several factors: the permeability and thickness of the material, temperature, and pressure difference across the containment layer. [103] All metals are highly permeable to hydrogen; some leakage will occur even on thick walls. Any imperfections during manufacturing can cause the whole system to leak hydrogen. The material's resistance to leakage is only as strong as the weakest link. The presence of welds, seals, valves, and fittings poses significant challenges for designing hydrogen infrastructure. [104]

Failure to properly contain hydrogen inside closed buildings can lead to a concentration buildup above 4 %. [104] The leakage issue is a big problem because it is hard to detect by humans as hydrogen gas is colorless and odorless. Several types of injuries are possible when humans are present during leaks, fires, or explosions. Asphyxiation may occur when hydrogen displaces oxygen below 19.5 % by volume. Hydrogen fire is invisible to the human eye but can cause severe burns. [104]

Thus, it is essential to detect containment breaches with alarm systems to notify the staff. One way to detect hydrogen leaks is with sensors. They can detect leaks at a distance using refractive index imaging techniques or ultrasonic detection devices. [105] Another method is to monitor hydrogen pressures inside the systems and raise alarm when unexpected drop in pressure is detected.

Contingency plans must be developed during the design and construction phases of the hydrogen data center. The staff must be familiar with safety procedures, and automated mitigation procedures must be implemented. Furthermore, the electrical infrastructure must be isolated from areas of potential hydrogen leaks, as high-power electrical systems and easily combustible gas are a dangerous combination. It is critical to design infrastructure that will fail safely and predictably.

5 Modeling

Mathematical modeling of the system components for low-temperature and high-temperature design will be performed. A simplified approach to modeling from the infrastructure standpoint is performed. The provided models and interpolations are sufficient to evaluate the performance of the chosen hydrogen-based components. Two methods are used to solve PEM fuel cells, ARS is calculated through interpolation of plots, and burner fuel consumption and district heating are solved for each design. Properties of hydrogen used in calculations are outlined in Table 5.1.

Property	Value
Molecular weight	2.016 mol
Higher Heating Value	119.96 MJ kg^{-1}
Lower Heating Value	141.88 MJ kg^{-1}

Table 5.1: Relevant properties of hydrogen gas. [106]

5.1. PEM Fuel Cell

A generic fuel cell model will be developed to relate IT load to waste heat generation, hydrogen consumption, and water production. PEM fuel cells can be evaluated using two different methods: voltage and efficiency.

The voltage method uses cell voltage as a variable to solve the model. This method evaluates the values of an ideal fuel cell and works well for LT-PEM fuel cells operating at optimal temperatures. [107] Concepts of stoichiometric chemical balance, energies of chemical reactions, and Gibbs's free energy are applied to construct the model. [107]

The efficiency method requires the electrical efficiency of the fuel cell to evaluate for the same unknowns. This method assumes that all energy that did not result in electricity production is released as waste heat. [78, 108] The guiding principle of this assumption is the law of conservation of energy. [108] PEM fuel cell utilizes the energy stored inside the hydrogen molecule in 3 ways: 50 % of H_2 energy is used to produce electricity, 45 % is converted to heat, while the last 5 % is not utilized due to unreacted hydrogen. [108] The efficiency method is more generic and can be applied to any electricity-generating system but with less assurance for the correctness of the result in fuel cell applications specifically. Concepts of conservation of energy and specific enthalpy are applied.

The following operation conditions are assumed for both designs:

- The fuel cell operates at normal temperature and pressure.
- The fuel cell operates at a steady state.
- Sufficient cooling is provided to the fuel cell.

- No thermal energy is lost to the environment.
- Electrical load is constant, $P_{\mathrm{IT}} = 1 \times 10^6$ W.
- Efficiency of the DC power converter is constant, $\eta_{\mathrm{dc}} = 0.95$.
- Recovery rate of purification is constant, $\eta_{\mathrm{yield}} = 0.95$.

It is important to note that the calculations assume a 100 % utilization of the servers. In practice, the utilization rate is low at around 25 %. [109] Research suggests that up to 60 % of operational costs can be saved if the system is rightsized to the actual power requirements. [110]. Running the data center at high utilization poses risks that decrease reliability. [109] Balance between expected risk and cost should be dependent on the overall SLA metrics. [109] It could be beneficial to strategically increase server utilization rates for greater savings to improve costs, similarly to how running servers at higher temperatures greatly improved cooling spending. For the partial cost calculations performed in this study, a 100 % utilization rate will suffice. [109] However, it is recommended to try running the infrastructure at 40 – 60 % capacity for cost savings.

5.1.1. Voltage Method

The fuel cell reaction formula is defined in Equation 5.1, which represents the reversible chemical reaction of hydrogen and oxygen combining to form water, while releasing electricity and heat.

$$2\,\mathrm{H_2} + \mathrm{O_2} \longrightarrow 2\,\mathrm{H_2O} + \mathit{electricity} + \mathit{heat} \tag{5.1}$$

Equation 5.2 relates the electrical power output of the fuel cell to the current within the cell stack. [107]

$$P_{\mathrm{IT}} = \frac{V_{\mathrm{fc}} \cdot I_{\mathrm{fc}} \cdot n_{\mathrm{fc}}}{\eta_{\mathrm{dc}}} \tag{5.2}$$

The power output P_{IT} is determined by the fuel cell voltage V_{fc}, current I_{fc}, and the number of fuel cells in the stack n_{fc}. Additionally, the equation incorporates η_{dc} to account for DC/DC losses of power conversion. Individually, each fuel cell operates at very low voltages. Therefore, increasing the stack size n_{fc} is beneficial for boosting the voltage output and reducing resistive power losses. It is assumed that the appropriate value will be chosen for the required load.

The estimation of mass flow rates of hydrogen and oxygen is derived from chemical balance Equation 5.1 and is presented in Equation 5.3.

$$\dot{m} = \frac{I_{\mathrm{fc}} \cdot n_{\mathrm{fc}}}{2 \cdot F \cdot \eta_{\mathrm{dc}}} \quad \mathrm{mol\,s^{-1}} \tag{5.3}$$

Where $\dot{m}$ denotes mass flow rate, F is Faraday constant (96 485 C/mol). Equation 5.2 and 5.3 are combined into Equation 5.4 to get a relationship between the hydrogen mass flow rate and produced IT power.

$$\dot{m}_{\mathrm{H_2,fc}} = \frac{P_{\mathrm{IT}}}{2 \cdot V_{\mathrm{fc}} \cdot F \cdot \eta_{\mathrm{dc}}} \quad \mathrm{mol\,s^{-1}} \tag{5.4}$$

Where $\dot{m}_{\mathrm{H_2,fc}}$ is the molar hydrogen consumption rate of the fuel cell. The molar mass of hydrogen is 2.02×10^{-3} kg mol^{-1}; therefore, Equation 5.4 is converted to a unit of kilogram per second and simplified, resulting in Equation 5.5

$$\dot{m}_{\mathrm{H_2,fc}} = 1.05 \cdot 10^{-8} \cdot \frac{P_{\mathrm{IT}}}{V_{\mathrm{fc}} \cdot \eta_{\mathrm{dc}}} \quad \mathrm{kg\,s^{-1}} \tag{5.5}$$

The water production rate is derived using the same Equation 5.4 as for hydrogen consumption rate, since the molar production rate of H_2O is the same as the molar production rate of H_2. The molar mass of water is 9.34×10^{-8} kg mol^{-1}, therefore Equation 5.3 is converted to the unit of kilogram per second and simplified, resulting in Equation 5.6. [107].

$$\dot{m}_{\mathrm{H_2O,fc}} = 9.34 \cdot 10^{-8} \cdot \frac{P_{\mathrm{IT}}}{V_{\mathrm{fc}} \cdot \eta_{\mathrm{dc}}} \quad \mathrm{kg\,s^{-1}} \tag{5.6}$$

Where $\dot{m}_{\mathrm{H_2O,fc}}$ is the water production rate of the fuel cell. The efficiency of the fuel cell is directly correlated with operational voltage. [107] Equation 5.7 is used to calculate fuel cell efficiency. [107]

$$\eta_{\mathrm{fc}} = \frac{V_{\mathrm{fc}}}{1.48} \tag{5.7}$$

The value of 1.48 is constant because it is the maximum electrical potential of the chemical reaction of Equation 5.1, where the water product remains in the liquid form during the reaction. [107]

Equation 5.8 is then used to calculate the waste heat produced. [107].

$$\dot{Q}_{\mathrm{fc}} = 0.5 \cdot F \cdot \Delta h_{LHV} \cdot n_{\mathrm{fc}} - I_{\mathrm{fc}} \cdot V_{\mathrm{fc}} \cdot n_{\mathrm{fc}} \tag{5.8}$$

Where $\dot{Q}_{\mathrm{fc}}$ is the thermal heat rate of the fuel cell and Δh_{LHV} is the lower heating value of hydrogen. LHV is used because all resultant water is in vapor form. [111] The Equation 5.8 can be simplified into Equation 5.9.

$$\dot{Q}_{fc} = (1.254 - V_{\mathrm{fc}}) \cdot I_{\mathrm{fc}} \cdot n_{\mathrm{fc}} \tag{5.9}$$

Finally, Equation 5.9 is rewritten in terms of power output, resulting in the final Equation 5.10 for the hydrogen fuel cell. [107]

$$\dot{Q}_{fc} = P_{\mathrm{IT}} \cdot \left(\frac{1.254}{V_{\mathrm{fc}}} - 1 \right) \tag{5.10}$$

5.1.2. Efficiency Method

First, the total energy amount of energy required to fulfill the electrical output of P_{IT} is found using Equation 5.11 The total energy required for fuel cell operation is the inverse of the fuel cell and DC power converter efficiency.

$$P_{\mathrm{fc,total}} = \frac{P_{\mathrm{IT}}}{\eta_{\mathrm{fc}} \cdot \eta_{\mathrm{dc}}} \tag{5.11}$$

Where $P_{\mathrm{fc,total}}$ is the total energy released by hydrogen fuel during operation at P_{IT} load, η_{fc} is the efficiency of the fuel cell, and η_{dc} is power converter efficiency. Then the energy rate is expressed in terms of hydrogen mass flow rate in Figure 5.12.

$$\dot{m}_{\mathrm{H_2,fc}} = \frac{P_{\mathrm{fc,total}}}{\Delta h_{\mathrm{LHV}}} = \frac{P_{\mathrm{IT}}}{\eta_{\mathrm{fc}} \cdot \eta_{\mathrm{dc}} \cdot \Delta h_{\mathrm{LHV}}} \tag{5.12}$$

Where $\dot{m}_{\mathrm{H_2,fc}}$ is hydrogen the consumption rate in kg s^{-1}. The lower heating value of hydrogen is used again.

Applying the aforementioned law of conservation of energy results in Equation 5.13, which relates the power of waste heat $\dot{Q}_{\mathrm{fc}}$ to the electrical load P_{IT}. The electrical (η_{fc}) and thermal ($1 - \eta_{\mathrm{fc}}$) efficiency are used as scaling factors. The efficiency of power conversion is also added.

$$\frac{\dot{Q}_{fc}}{1 - \eta_{\mathrm{fc}} \cdot \eta_{\mathrm{dc}}} = \frac{P_{\mathrm{IT}}}{\eta_{\mathrm{fc}} \cdot \eta_{\mathrm{dc}}} \tag{5.13}$$

Equation 5.13 is then solved to find the waste heat production rate, as shown in Equation 5.14.

$$\dot{Q}_{fc} = P_{IT} \cdot \left(\frac{1}{\eta_{fc} \cdot \eta_{dc}} - 1 \right) \tag{5.14}$$

The molar mass differences between hydrogen and water can be used to estimate the amount of water produced. According to Equation 5.1, one consumed hydrogen molecule reacts with one water molecule. Molar mass of H_2 is approximately 2.016 g mol^{-1} and the molar mass of H_2O is 18.015 g mol^{-1}. A conversion factor is calculated to relate their quantities, leading to the derivation of Equation 5.15.

$$\dot{m}_{H_2O,fc} = 8.936 \cdot \dot{m}_{H_2,fc} \tag{5.15}$$

5.2. Absorption Refrigeration System

To evaluate the performance of the ARS without modeling the complete thermodynamic cycle, temperatures of the two major components of the ARS during steady-state operation need to be determined. It was previously established in Section 2.3.3 that the optimal server room temperature to fulfill Class A cooling requirements and achieve energy savings is between 18 and 27 °C. Generally, the temperature difference between the cooled space and the evaporator is 5 – 10 °C. [112] Therefore, the optional evaporator temperature T_{evap} must be between 8 and 22 °C. A reasonable temperature of 10 °C is chosen from the evaporator of the absorption cycle. The temperature of the generator T_{gen} is assumed to be fixed to the output temperature of the fuel cell T_{fc}.

Industry-standard measurement of the cooling capacity of the refrigeration systems is in the imperial units of "ton of refrigeration." Conversion to metric units is accomplished with Equation 5.16. [29]

$$1 \text{ ton of refrigeration} = 3.517\,\text{kW} \tag{5.16}$$

An in-depth literature review was performed to evaluate the performance characteristics of the ARS thermodynamic cycles. Researchers from Yazd University modeled the thermodynamic performance of various common configurations from half to triple-absorption refrigeration systems. [113] The researchers found that increasing evaporator temperatures increases COP of the system, as well as lowering required generator temperature. [113]. The plots of their studies are presented in Figure 5.1 and Figure 5.2 for single-effect and double-effect cycles respectively. Their mathematical model used a 300 kW evaporator load. Other studies of absorption refrigeration systems confirm the relationship between generator temperature and COP. [114, 115, 116, 112]

An extra verification step is needed to safely interpolate COP from generator temperatures. Research on COP correlations for various sizes of single-effect vapor absorption refrigeration systems concludes that cooling capacity has little effect on the final performance. [117] Systems operating at 350 kW, 3500 kW, and 35 000 kW cooling loads behave similarly with relation to generator temperature, and their performance is within 5 – 8 % of each other. [117] Therefore, it is safe to assume that generator temperature vs. COP figures are accurate for the feasibility study.

The formula relating to the COP of an absorption refrigeration system to evaporator and generation temperatures is found with Equation 5.17.

$$\text{COP} = \frac{\dot{Q}_{evap}}{\dot{Q}_{gen} + \dot{W}_{pump}} \tag{5.17}$$

Where $\dot{Q}_{evap}$ is the heat transfer rate of the evaporator, $\dot{Q}_{gen}$ is the heat transfer rate to the generator, and $\dot{W}_{pump}$ is the power of the internal pump, which is neglected during calculations.

5.2.1. Single-effect

According to Figure 5.1, the single-stage effect system has a coefficient of performance of less than one. Therefore, the addition of extra heat $\dot{Q}_{burn}$ is required to achieve sufficient cooling. A direct-fired ARS that uses hydrogen fuel as a heat source is required, and the consumption rate of the fuel needs to be calculated. The coefficient of performance of single-effect ARS is approximately 0.8 from interpolation of Figure 5.1.

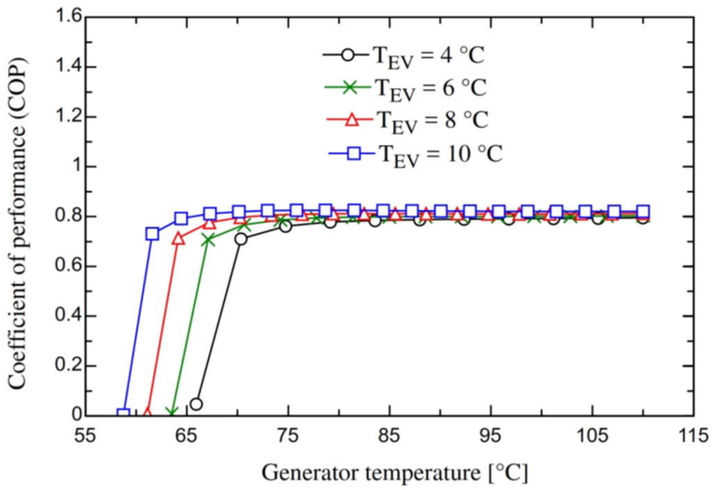


Figure 5.1: COP performance of single effect ARS. [113]

The total power supplied to the generator is the sum of the fuel cell's waste heat and the hydrogen burner. Using Equation 5.17 and substituting the combined heat rate for the generator results in Equation 5.18

$$\mathrm{COP} = \frac{\dot{Q}_{evap}}{\dot{Q}_{fc} + \dot{Q}_{burn}} \tag{5.18}$$

The evaporator's rate of heat transfer $\dot{Q}_{evap}$ is substituted with power usage of the IT equipment P_{IT} according to the previous assumption that IT equipment acts as a perfect resistive heater and produces heat at the same rate as it consumes electricity. Rearranging for heat transfer of the direct-fired burner $\dot{Q}_{burn}$ results in Equation 5.19.

$$\dot{Q}_{burn} = \frac{P_{IT}}{\mathrm{COP}} - \dot{Q}_{fc} \tag{5.19}$$

The rate of burning hydrogen is computed using Equation 5.20. A higher heating value is used for combustion because the energy will be used in its entirety and condense the water vapor, recovering the latent heat used during combustion.

$$\dot{m}_{H_2,burn} = \frac{\eta_{burn} \cdot \dot{Q}_{burn}}{\Delta h_{HHV}} \tag{5.20}$$

Where $\dot{m}_{H_2,burn}$ is the consumption rate of the hydrogen burner in $\mathrm{kg\,s^{-1}}$, η_{burn} is an efficiency of combustion, and Δh_{HHV} is the higher heating value of hydrogen. Equation 5.19 and Equation 5.20 are combined into Equation 5.21 to find the mass transfer rate of hydrogen in the direct firing burner in terms of the IT load.

$$\dot{m}_{H_2,burn} = \frac{\eta_{burn}}{\Delta h_{HHV}} \left(\frac{P_{IT}}{\mathrm{COP}} - \dot{Q}_{fc} \right) \tag{5.21}$$

5.2.2. Double-effect

Modeling of the double-effect ARS follows the same assumptions as for the single-effect configuration. The coefficient of performance for the double-effect ARS is approximately 1.3, as determined from Figure 5.2. The coefficient of performance is greater than 1; therefore, using a burner is unnecessary. With a modern double-stage ARS, the cooling capacity can be redirected toward district heating. The waste heat can be represented with Equation 5.22.

$$\dot{Q}_{\mathrm{district}} = \dot{Q}_{\mathrm{fc}} \cdot \mathrm{COP} - \dot{Q}_{\mathrm{IT}} \quad \mathrm{kg\,s^{-1}} \tag{5.22}$$

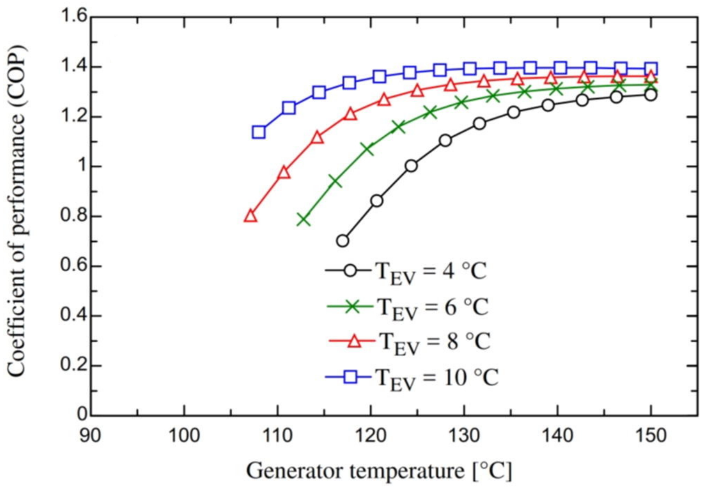


Figure 5.2: COP performance of double-effect ARS. [113]

5.3. Purification

The low-temperature design requires the purification of pipeline hydrogen. The purification step can be modeled using yield rate efficiency η_{yield}. This calculation step is applied after the mass flow rate of hydrogen is found. The recovery rate of is applied to both fuel cell and burner hydrogen consumption. Equation 5.23 shows how the values are calculated.

$$\dot{m}_{\mathrm{H_2,raw}} = \frac{\dot{m}_{\mathrm{H_2,pure}}}{\eta_{\mathrm{yield}}} \tag{5.23}$$

Where $\dot{m}_{\mathrm{H_2,pure}}$ is mass flow rate of purified hydrogen and $\dot{m}_{\mathrm{H_2,raw}}$ is mass flow rate of hydrogen prior to purification.

5.4. Results

Low-temperature design utilizing LT-PEM fuel cell and single-effect ARS with hydrogen burner is evaluated at a standard voltage of 0.65 V for voltage method [107] and 50 % efficiency for the efficiency method [108]. The results of both methods are available in Table 5.2. The findings of the total hydrogen consumption rate and water production rate are consistent, indicating the validity of both methodologies. The only discrepancy is in waste heat rates — the efficiency model results in much higher values to the point where the hydrogen burner is almost unnecessary. The results of the voltage calculations will be used in the subsequent economic evaluation.

Evaluation of the high-temperature designs utilizing HT-PEM fuel cells and double-effect ARS will use the same equations for fuel cell calculations as the low-temperature design. Research suggests that operating temperature has a moderate effect on the operating voltage [73] An assumption is made that the operation of HT-PEM fuel cell is analogous to LT-PEM. The results of the calculations are available in Table 5.3.

Symbol	Voltage Method (V_{fc} = 0.65)	Efficiency Method (η_{fc} = 0.45)	Unit	Description
$\dot{m}_{H_2,fc}$	0.0179	0.0185	$kg\,s^{-1}$	Fuel cell hydrogen consumption rate
$\dot{m}_{H_2,burn}$	0.001 96	0.001 02	$kg\,s^{-1}$	ARS hydrogen consumption rate
$\dot{m}_{H_2,total}$	0.0199	0.0195	$kg\,s^{-1}$	Total hydrogen consumption rate
$\dot{m}_{H_2O,fc}$	0.151	0.157	$kg\,s^{-1}$	Fuel cell water production rate
η_{fc}	43.92	50	%	Fuel cell electrical efficiency
$\dot{Q}_{fc}$	972	1105	$kW\,s^{-1}$	Fuel cell waste heat produced

Table 5.2: Low temperature design calculation results.

Symbol	Voltage Method (V_{fc} = 0.65)	Efficiency Method (η_{fc} = 0.45)	Unit	Description
$\dot{m}_{H_2,fc}$	0.0170	0.017 55	$kg\,s^{-1}$	Fuel cell hydrogen consumption rate
$\dot{m}_{H_2,burn}$	0	0	$kg\,s^{-1}$	ARS hydrogen consumption rate
$\dot{m}_{H_2,total}$	0.0170	0.017 55	$kg\,s^{-1}$	Total hydrogen consumption rate
$\dot{m}_{H_2O,fc}$	0.151	0.157	$kg\,s^{-1}$	Fuel cell water production rate
η_{fc}	43.92	50	%	Fuel cell electrical efficiency
$\dot{Q}_{fc}$	972	1105	$kW\,s^{-1}$	Fuel cell waste heat produced

Table 5.3: High temperature design calculation results.

The water production rate of the fuel cell is particularly high. Specifically, the rate of 0.151 $kg\,s^{-1}$ translates to 543 $kg\,h^{-1}$, or simply 543 liters per hour. This is not a mistake, as 1 kWh fuel cell produces about 0.5 L of water. [107] The large amount of water produced by the fuel cell could be difficult to manage. However, when reusing it internally, the fuel cell's water byproduct will greatly reduce the quantities of water purchased from the utilities, resulting in better WUE metrics. Greatly reducing water consumption contributes effectively to the overall sustainability of the proposed hydrogen-powered data center.

6 Economics

The costs associated with the proposed infrastructure design of the hydrogen-powered data center will be evaluated. Ideally, traditional pricing should be used as a baseline for comparison. Unfortunately, obtaining accurate costs of the existing data centers is challenging due to the secretive nature of the industry. The lack of publicly available data regarding infrastructure components is a major roadblock to drawing concrete comparisons. The quality comparison is further impeded by the high degree of uncertainty of any data center financial model. [109] These models have infinite variables to choose from, leading to a subjective outcome. [109] It is suggested that 70 – 80 % of the costs of the data center deployment are intangible costs — a hidden cost that is hard to quantify objectively. [109] Furthermore, the price of components varies depending on purchasing volume and can range from 5 % to 30 %. [109]

Economic viability is evaluated in the industry through an industry-standard metric Total Cost of Ownership (TCO). [118] The TCO evaluation attempts to create a financial model to capture all costs, including hidden intangible costs. These costs are usually derived from previous deployments, which provide ballpark cost information for the new data center. [118] Figure 6.1 shows the breakdown of the infrastructure costs relating to electricity and cooling only.

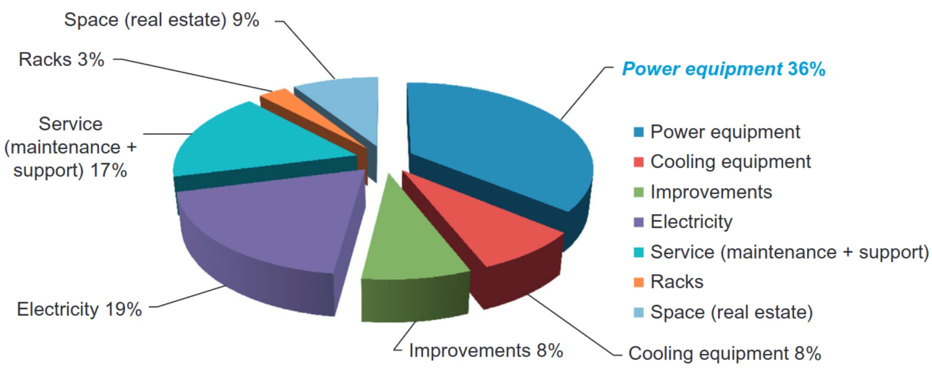


Figure 6.1: TCO breakdown for traditional data center. [119]

With all these factors in mind, the best-effort approach to economic modeling for infrastructure components will be performed. Uncertainty of the final results is reduced as the costs associated with construction and decommissioning are ignored. Some typical costs, which are the same for traditional and hydrogen data centers, are not accounted for. Since hydrogen data center infrastructure is at the core of this research, the servers are not included in the calculations. The price of IT equipment can vary widely, and the choice is left up to the owner, contributing around 30 % to the total cost. [118] Costs not included in the calculations are listed below but are not limited to:

- Land acquisition.
- Supporting utilities (fiber internet, water supply, electricity transmission lines, fuel pipelines).
- IT hardware and software.
- Building construction.
- Permits (building, electrical, fire, environmental, zoning, hazardous materials).
- Fire suppression systems.
- Staffing costs.
- Taxes (property, revenue).

The expenses are split into two major categories: Capital Expenditures (CapEx) and Operating Expenses (OpEx). [118] CapEx categorizes one-time costs of purchasing the infrastructure equipment. [118] OpEx relates to spendable resources and maintenance costs. CapEx and OpEx costs of the infrastructure components were found and are available in Table 6.1 and Table 6.2, respectively. It is important to note that the CapEx and OpEx numbers strongly depend on the data center's tier level. [118] The calculations are performed with the modeling results of Chapter 5.

The economic study will evaluate two different designs: low-temperature design (LT-PEMFC + single-effect ARS) and high-temperature design (HT-PEMFC + double-effect ARS). Both designs are computed in terms of current costs in 2024 and projected costs in 2030. Therefore, four scenarios are compared. In charts, low-temperature is shortened to LT, and high-temperature is abbreviated as HT.

6.1. CapEx

Values in Table 6.1 will used to evaluate CapEx. The units of the cooling system were converted from \$/ton to \$/kW using Equation 5.16. The CapEx costs are evaluated by summing per megawatt cost of all the components for each design. CapEx results are evaluated in units of Million \$/MW. The unit of cost per megawatt aligns nicely with the proposed module size. At face value, the result represents the purchase costs of the supporting infrastructure for a single module. The final results of CapEx are plotted in Figure 6.2.

Component	**Current Cost (2023)**	**Projected Cost (2030)**	**Source**
LT-PEM Fuel Cell (\$/kW)	2000	1000	[83]
HT-PEM Fuel Cell (\$/kW)	3000	2000	[120]
Single-effect ARS (\$/ton)	0.2	0.2	[121]
Double-effect ARS (\$/ton)	0.3	0.3	[121]

Table 6.1: CapEx variables of infrastructure components.

6.2. OpEx

Solving for OpEx involves more granular calculations. The recurring costs of fuel cell and ARS components include maintenance as well as hydrogen fuel consumption rates. Table 6.2 outlines associated costs for each component. Hydrogen consumption rates found in Chapter 5 are used to evaluate hydrogen fuel costs. Approximation of hydrogen costs is difficult to do with certainty, as the scale of the hydrogen economy in the Netherlands will be dictated by the success or failure of the hydrogen pipeline project. The values found during market research are reasonable, with hydrogen reaching the price of \$2/kg by 2030. Research suggests that due to economies of scale, green hydrogen production can drop to a low value of \$1/kg. [21] The maintenance cost of the fuel cell is calculated on the assumption that it must be completely replaced at CapEx cost after it reaches its operational lifespan. [120] For hydrogen transport costs, a distance of 25 kilometers is used. The results are plotted in Figure 6.3.

Component	Current (2024)	Projected (2030)	Source
LT-PEM fuel cell lifespan (hr)	40 000	80 000	[83]
HT-PEM fuel cell lifespan (hr)	10 000	20 000	[120]
Single-effect ARS ($/ton – hr)	0.2	0.2	[121]
Double-effect ARS ($/ton – hr)	0.3	0.3	[121]
Hydrogen gas cost ($/kg)	5	2	[83]
Hydrogen transport cost ($/kg/100km)	0.5	0.2	[48, 21]

Table 6.2: OpEx variables of infrastructure components.

6.3. Results

Figure 6.2 and Figure 6.3 graphically demonstrate the difference between the CapEx and OpEx of the four scenarios, respectively.

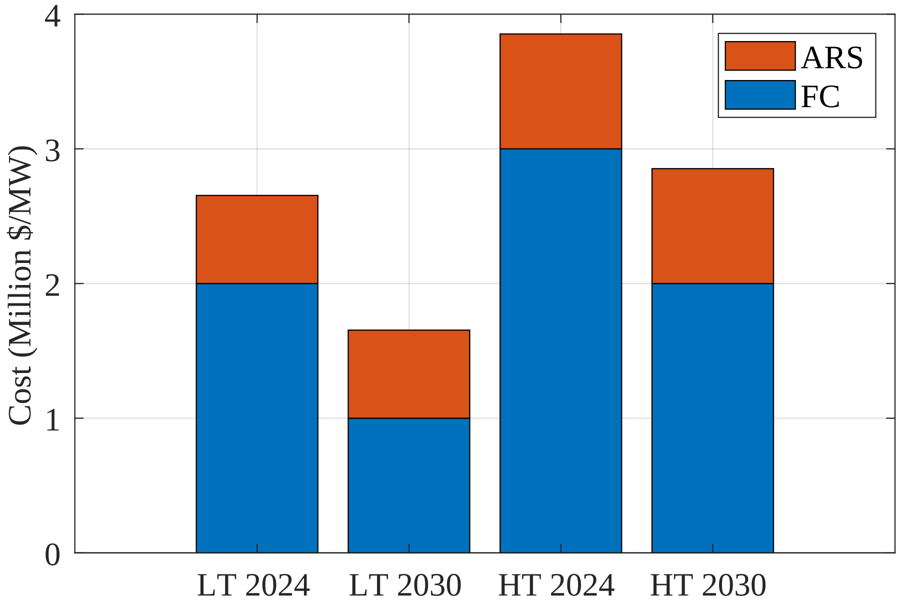


Figure 6.2: CapEx results for different scenarios.

In terms of CapEx, the fuel cell systems are expected to drop in price rapidly as hydrogen technologies become commonplace. [21] The economic evaluation demonstrates a discount for a co-generation system of approximately 37.6 % for low-temperature and 26.0 % for high-temperature designs by 2030. The steeper discount rate is observed on low-temperature systems due to the already large-scale manufacturing of LT-PEM fuel cells in 2024. In general, the high-temperature design is more expensive. Due to research and the pre-production status of HT-PEM technologies, the prices of these fuel cells will take a long time to reach equilibrium with LT-PEM. Refrigeration-wise, the costs of double-effect chillers are slightly higher than single-effect ones, but the overall difference in price is insignificant. A low-temperature design is recommended to minimize CapEx costs.

The projected operational expenses for both designs demonstrate substantial cost reductions by 2030. Unfortunately, the costs of high-temperature designs are prohibitively high due to frequent fuel cell stack maintenance. The early adopter prices for the technology are steep. However, similarly to the CapEx calculations, the low-temperature design achieves greater operational cost efficiency. The mass-produced LT-PEM fuel cells for stationary applications have impressive operational lifetimes, reducing maintenance costs to a small percentage of total spending. In low-temperature design: hydrogen fuel is a major contributor to costs, accounting to 77.4 % and 67.9 % of total recurrent spending in 2024 and 2030 respectively. High spending on fuel signifies that the hydrogen cogeneration system is efficient. By 2030, operational costs are expected to reach $208/MWh, making this hydrogen data center design

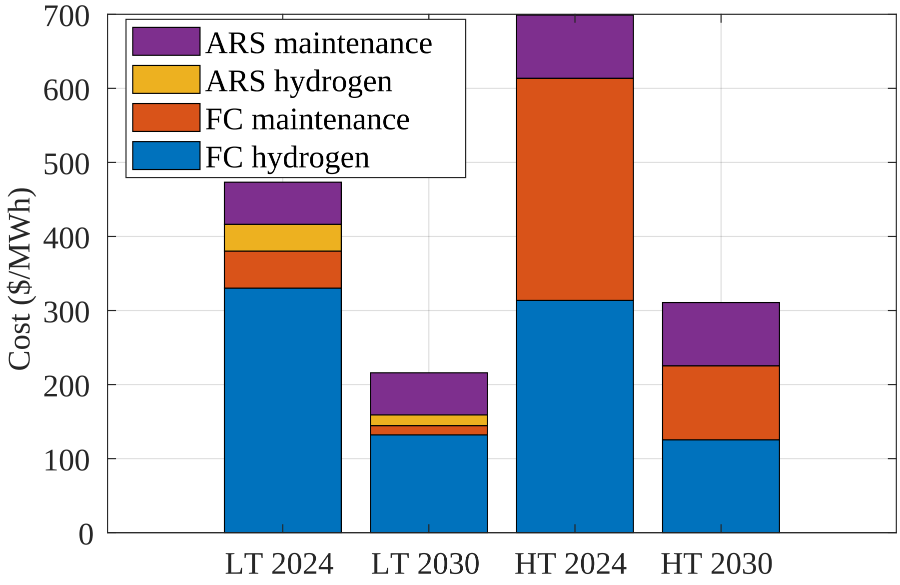


Figure 6.3: OpEx results for different scenarios.

competitive with traditional data centers. Decrease in costs of hydrogen fuel is a key speculation for success of the proposed designs.

It is essential to compare the costs of a hydrogen-powered data center with those of a traditional data center. However, due to the secretive nature of the data center industry, an accurate megawatt-for-megawatt comparison of CapEx and OpEx is impossible from publicly available data. Therefore, only the "operational fuel" costs can be compared. Specifically, the electricity costs of operating 1 megawatt of servers in a traditional center will be compared to the equivalent amount of hydrogen consumed for the proposed modular design.

As of 2022, a company, DC1, which provides rack spaces for rent in their data centers, charges 32 cents per kWh in Amsterdam and 24 cents per kWh in Oude Meer. [122] These costs are consistent with the average electricity prices in the Netherlands, as estimated from the average rates of variable energy contracts from the 19 largest energy suppliers. [123] As of August 2024, the average cost of electricity is 31 cents per kWh. [123] For simplicity, a rounded value of 30 cents per kWh will be used in this analysis. Applying the current conversion rate of 1 EUR = 1.10 USD and converting the units to MWh results in a price of $330/MWh.

The costs associated with hydrogen consumption are provided in Table 6.3. The economics of grid electricity and hydrogen may change dramatically by 2030, but the current electricity prices can allow a comparison. As of August 2024, the operational fuel costs for traditional and hydrogen data centers are similar. However, the reduction of hydrogen price from $5/kg to $2/kg by 2030 results in sizeable cost savings of around 50 %.

Design \ Time	Current (2024)	Projected (2030)
Low Temperature	366.4	146.6
High Temperature	313.7	125.5

Table 6.3: Hydrogen fuel costs in $/MWh.

This simple comparison indicates that hydrogen could be a highly effective cost-saving solution for data center use. Despite these findings, it is essential to acknowledge that the results are highly speculative. Rates of grid electricity and hydrogen are uncertain in the future. For example, grid electricity prices could also decrease due to the deployment of renewables, which have lower running costs.

Other noteworthy findings of the economic analysis are provided in Table 6.4. The table outlines noteworthy values for a proposed 1 MW module over the course of a year.

Description	**Value**
OpEx LT 2024	\$4.15 million
OpEx LT 2030	\$1.89 million
OpEx HT 2024	\$6.13 million
OpEx HT 2030	\$2.72 million
Hydrogen consumption LT	626.7 tH_2
Hydrogen consumption HT	536.4 tH_2
Hydrogen costs 2024	\$3.21 million
Hydrogen costs 2030	\$1.28 million

Table 6.4: Findings of economic analysis: total yearly metrics for 1 MW module.

7
Conclusion

This study demonstrates that building a reliable data center that uses hydrogen as the only fuel source is possible. Two designs operating at low and high temperatures were proposed. The study identified opportunities and challenges of hydrogen-based data center infrastructure.

Some technologies of the traditional data center designs can be applied to the hydrogen-only approach. For instance, a raised-floor pendulum hot-isle/cold-isle server room layout should be implemented. Compartmentalization principles should be applied at the infrastructure level. Methodologies regarding the redundancies of the distribution paths must be utilized. The proposed design conforms to tier II reliability guidelines and is theorized to provide a sufficient level of reliability.

One significant benefit of using hydrogen in a data center environment is the small footprint of the infrastructure. The fuel cells, absorption refrigeration system, and UPS occupy minimal space due to their high energy density. The modular design increases portability, allowing deployments in different locations. Furthermore, the proposed 1-megawatt infrastructure module is tileable, enabling straightforward deployment scaling.

Another benefit is zero CO_2 emissions during operation. A preemptive focus on avoiding carbon taxes could reduce long-term costs compared to traditional fossil-powered data centers. With hydrogen as an energy carrier, operational reliability in the sustainable future can be preserved, while traditional data centers could struggle with intermittent renewable energy. Furthermore, hydrogen's favorable properties make it convenient to store, eliminating the need for expensive chemical batteries. The pipeline supply method is sufficient for large-scale operations of the proposed design. Moreover, the dual hydrogen supply from the pipeline and backup high-pressure storage allow for potentially indefinite, uninterruptible operation.

The proposed design greatly simplifies the infrastructure components, reducing upfront investment, lowering running costs, and increasing reliability. DC bus improves operational efficiency, while the cogeneration system utilizes fuel efficiently and minimizes energy use for cooling. The cogeneration system proposed in this study has demonstrated feasibility and high efficiency in both academic studies and real-world experiments.

Unfortunately, the hydrogen-only data center infrastructure has its challenges. Firstly, a physical prototype of a hydrogen-only data center does not exist, meaning that the proposed system has yet to be tested and validated. It may take a long time for the data center operators to green-light the infrastructure design for use by clients with stringent service level agreements. Secondly, the uncertainty surrounding the future hydrogen economy poses a risk for early adopters. The high costs of pioneering hydrogen technology, often called the "early adopter tax," introduce risks and financial barriers to entry. Close collaboration between multiple companies and stakeholders introduces challenges in developing a megawatt-scale cogeneration system. Thirdly, the simplified infrastructure, specifically the DC bus, necessitates using different power supply units inside the servers. Deviating from the industry-standard electrical norms could be a barrier to entry for some data center tenants. Lastly, hydrogen is difficult to work with as it is inherently more dangerous than electricity or natural gas. The data center must be designed with extra emphasis on safety to avoid catastrophic incidents that could endanger human lives, damage the company's reputation, and lead to significant financial losses.

The low-temperature design is more economically viable than the high-temperature design. The necessary fuel cell and absorption cooling systems are available for purchase today, and their costs are rapidly decreasing as production volumes ramp up. Unfortunately, the purification system required to filter the industrial-grade hydrogen supplied by the pipeline is currently challenging to integrate. From an operational perspective, the low-temperature cogeneration control system is complex and requires real-world testing to ensure stable operation. The challenge of decoupling power and cooling to account for transient thermal behaviors is significant, but can be overcome with thorough testing and validation.

The high-temperature design is currently infeasible, as high-temperature fuel cell technology is still at the pre-production technological readiness level. Fortunately, existing research and commercial-grade prototypes of these fuel cells show strong future potential. The insensitivity of high-temperature fuel cells to impurities present in industrial hydrogen eliminates the need for purification, enabling data center deployments irrespective of available hydrogen quality. Another advantage of this cogeneration system is its high coefficient of performance, which ensures proper cooling of IT equipment and allows for cost savings through participation in district heating agreements.

The feasibility study could not make concrete comparisons with traditional data center technologies. Economic analysis is particularly difficult due to the secrecy within the ICT sector and its inherent levels of financial uncertainty. Hydrogen technology operates on different principles, making direct cost comparisons difficult. Reliability certifications only exist for traditional data centers, and reliability metrics can only be evaluated by real-world operations. While direct cost comparisons are challenging, hydrogen-powered data centers have the potential to achieve high reliability. The future hydrogen economy can revolutionize the landscape of IT infrastructure. Further research and development are needed to create a cleaner IT infrastructure for the interconnected world of tomorrow.

Future Work

- Develop a high-fidelity physics-based software simulation model of all infrastructure components. Evaluate the control systems under extreme operating conditions and injected faults.
- Perform standalone small-scale design and testing of the physical prototype of the cogeneration system. Ensure proper transient response of LT-PEMFC and single-effect direct-firing hydrogen ARS. Validate system performance under various synthetic IT loads.
- Conduct a small-scale test of the proposed low-temperature module. Include all real-world components such as the cogeneration system, UPS, CRAH, and computer room.

Bibliography

[1] Charles J. Corbett. "How Sustainable Is Big Data?" In: *Production and Operations Management* 27.9 (2018), pp. 1685–1695. DOI: https://doi.org/10.1111/poms.12837. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/poms.12837. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/poms.12837.

[2] Martijn Koot and Fons Wijnhoven. "Usage impact on data center electricity needs: A system dynamic forecasting model". In: *Applied Energy* 291 (2021), p. 116798. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2021.116798.

[3] IEA. *Data Centres and Data Transmission Networks*. 2023. URL: https://www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks (visited on 03/17/2024).

[4] George Kamiya. *Data centres, energy efficiency, and energy transitions*. Tech. rep. 2021. URL: https://www.ca-eed.eu/wp-content/uploads/2022/01/IEA-CA-EED-Data-Centre-Workshop-11-2021-1.pdf (visited on 03/17/2024).

[5] John H. Seader PE Vince Renaud PE W. Pitt Turner IV PE and Kenneth G. Brill. *Tier Classifications Define Site Infrastructure Performance*. White Paper. 2008. URL: https://fsta.dk/wp-content/uploads/2023/07/Bilag-2-TUI3026ETierClassificationsDefineSiteInfrastructure.pdf.

[6] Fortinet. *What is a Colocation Data Center? Types & Benefits | Fortinet*. URL: https://www.fortinet.com/resources/cyberglossary/colocation-data-center (visited on 01/10/2024).

[7] Bill Kleyman. *Performance, Efficiency, and Sustainability: The New Cloud and Data Center Balance*. Tech. rep. 2021. URL: https://www.panduit.com/content/dam/panduit/en/solutions/NI-DC-DCF-cloud.pdf (visited on 02/23/2024).

[8] Caesar Wu and Rajkumar Buyya. "Chapter 11 - Cloud Infrastructure Servers: CISC, RISC, Rack-Mounted, and Blade Servers". In: *Cloud Data Centers and Cost Modeling*. Ed. by Caesar Wu and Rajkumar Buyya. Morgan Kaufmann, 2015, pp. 371–424. ISBN: 978-0-12-801413-4. DOI: https://doi.org/10.1016/B978-0-12-801413-4.00011-8. URL: https://www.sciencedirect.com/science/article/pii/B9780128014134000118.

[9] Katie Terrell Hanna. *How is U used as a measurment for servers?* 2021. URL: https://www.techtarget.com/searchdatacenter/definition/U (visited on 01/10/2024).

[10] Enconnex. *Server Rack Sizes & Dimensions: Depth, Width, & Height*. URL: https://blog.enconnex.com/exploring-server-rack-sizes-and-dimensions-depth-width-height (visited on 01/11/2024).

[11] Kazi Main Uddin Ahmed, Math H. J. Bollen, and Manuel Alvarez. "A Review of Data Centers Energy Consumption and Reliability Modeling". In: *IEEE Access* 9 (2021), pp. 152536–152563. ISSN: 2169-3536. DOI: 10.1109/ACCESS.2021.3125092. URL: https://ieeexplore.ieee.org/document/9599719.

[12] W. Pitt Turner IV Rob Menuet. *Continuous Cooling Is Required for Continuous Availability: Continuous Cooling Is Required for Continuous Availability*. Tech. rep. 2006. URL: http://wilsonengineered.com/Tech/TUI809ContinuousCooling_WP.pdf (visited on 04/03/2024).

[13] University of Arkansas. *Rack and Row Guideles | IT Services | University of Arkansas*. URL: https://its.uark.edu/about/policies/data-center/racks-rows-guidelines.php (visited on 01/11/2024).

[14] RackSolutions. *RackSolutions 48U Open Frame Rack for Data Center*. URL: https://www.racksolutions.eu/server-racks/open-frame-racks/data-center-openframe-rack-1.html (visited on 08/12/2024).

[15] RackSolutions. *RackSolutions 24U-48U Data Center Cabinet*. URL: https://www.racksolutions.eu/server-rack-enclosure.html (visited on 08/12/2024).

[16] CED Engineering. *HVAC Cooling Systems for Data Centers*. URL: https://www.cedengineering.com/userfiles/M05-020%20-%20HVAC%20Cooling%20Systems%20for%20Data%20Centers%20-%20US.pdf (visited on 04/26/2024).

[17] Yogesh Fulpagare and Atul Bhargav. "Advances in data center thermal management". In: *Renewable and Sustainable Energy Reviews* 43 (2015), pp. 981–996. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2014.11.056. URL: https://www.sciencedirect.com/science/article/pii/S1364032114009952.

[18] ENERGY STAR. *Recommendations for Measuring and Reporting Overall Data Center Efficiency*. 2011. URL: https://www.energystar.gov/sites/default/files/Data_Center_Metrics_Task_Force_Recommendations_V2.pdf (visited on 03/05/2024).

[19] Caesar Wu and Rajkumar Buyya. "Chapter 4 - Data Center Facilities". In: *Cloud Data Centers and Cost Modeling*. Ed. by Caesar Wu and Rajkumar Buyya. Morgan Kaufmann, 2015, pp. 153–191. ISBN: 978-0-12-801413-4. DOI: https://doi.org/10.1016/B978-0-12-801413-4.00004-0. URL: https://www.sciencedirect.com/science/article/pii/B9780128014134000040.

[20] John Roach. *Microsoft tests hydrogen fuel cells for backup power at datacenters*. 2020. URL: https://news.microsoft.com/source/features/sustainability/hydrogen-datacenters/ (visited on 02/24/2024).

[21] U.S. Department of Energy. *DOE National Clean Hydrogen Strategy and Roadmap*. Tech. rep. 2023. URL: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf?sfvrsn=c425b44f_5.

[22] Caesar Wu and Rajkumar Buyya. "Chapter 5 - Data Center Power". In: *Cloud Data Centers and Cost Modeling*. Ed. by Caesar Wu and Rajkumar Buyya. Morgan Kaufmann, 2015, pp. 193–225. ISBN: 978-0-12-801413-4. DOI: https://doi.org/10.1016/B978-0-12-801413-4.00005-2. URL: https://www.sciencedirect.com/science/article/pii/B9780128014134000052.

[23] Fawaz AL-Hazemi et al. "Dynamic allocation of power delivery paths in consolidated data centers based on adaptive UPS switching". In: *Computer Networks* 144 (2018), pp. 254–270. ISSN: 1389-1286. DOI: https://doi.org/10.1016/j.comnet.2018.08.004. URL: https://www.sciencedirect.com/science/article/pii/S1389128618307138.

[24] Caesar Wu and Rajkumar Buyya. "Chapter 6 - Power Distribution Unit and Cabling". In: *Cloud Data Centers and Cost Modeling*. Ed. by Caesar Wu and Rajkumar Buyya. Morgan Kaufmann, 2015, pp. 227–247. ISBN: 978-0-12-801413-4. DOI: https://doi.org/10.1016/B978-0-12-801413-4.00006-4. URL: https://www.sciencedirect.com/science/article/pii/B9780128014134000064.

[25] Emerson. *Power Distribution Considerations for Data Center Racks*. White Paper. 2010. URL: https://hf-files-oregon.s3.amazonaws.com/hdppowerqc_kb_attachments/2014/09-11/09e0e318-0966-45bd-bfb1-b0bde82f71ac/White%20Paper%20Power%20Distribution%20Considerations%20for%20Data%20Center%20Racks.pdf (visited on 03/17/2024).

[26] RMI. *Design Recommendations for High-Performance Data Centers*. 2003. URL: https://rmi.org/insight/design-recommendations-for-high-performance-data-centers/ (visited on 03/25/2024).

[27] Neil Rasmussen. *The Different Technologies for Cooling Data Centers*. White Paper 25. 2012. URL: http://www.apc.com/wp?wp=25.

[28] Neil Rasmussen. *Fundamental Principles of Air Conditioners for Information Technology*. White Paper 57. 2015. URL: http://www.apc.com/wp?wp=57.

[29] Caesar Wu and Rajkumar Buyya. "Chapter 7 - Data Center Cooling". In: *Cloud Data Centers and Cost Modeling*. Ed. by Caesar Wu and Rajkumar Buyya. Morgan Kaufmann, 2015, pp. 249–284. ISBN: 978-0-12-801413-4. DOI: https://doi.org/10.1016/B978-0-12-801413-4.00007-6. URL: https://www.sciencedirect.com/science/article/pii/B9780128014134000076.

[30] Caesar Wu and Rajkumar Buyya. "Chapter 9 - Cooling Strategy". In: *Cloud Data Centers and Cost Modeling*. Ed. by Caesar Wu and Rajkumar Buyya. Morgan Kaufmann, 2015, pp. 317–339. ISBN: 978-0-12-801413-4. DOI: https://doi.org/10.1016/B978-0-12-801413-4.00009-X. URL: https://www.sciencedirect.com/science/article/pii/B978012801413400009X.

[31] Energy Star. *Consider Water-Side Economizers*. URL: https://www.energystar.gov/products/data_center_equipment/16-more-ways-cut-energy-waste-data-center/consider-water-side (visited on 05/18/2024).

[32] Michael Goodwin. *What is an SLA (service level agreement)? | IBM*. 2024. URL: https://www.ibm.com/topics/service-level-agreement (visited on 02/23/2024).

[33] C. DeCusatis. "1 - Data center architectures". In: *Optical Interconnects for Data Centers*. Ed. by Tolga Tekin et al. Woodhead Publishing Series in Electronic and Optical Materials. Woodhead Publishing, 2017, pp. 3–41. ISBN: 978-0-08-100512-5. DOI: https://doi.org/10.1016/B978-0-08-100512-5.00001-2. URL: https://www.sciencedirect.com/science/article/pii/B9780081005125000012.

[34] Robert Arno et al. "Reliability of Data Centers by Tier Classification". In: *IEEE Transactions on Industry Applications* 48.2 (2012), pp. 777–783. DOI: 10.1109/TIA.2011.2180872. URL: https://ieeexplore-ieee-org.tudelft.idm.oclc.org/document/6111281.

[35] ASHRAE TC9.9 I. *Data Center Power Equipment Thermal Guidelines and Best Practices*. White Paper. 2016. URL: https://www.ashrae.org/File%20Library/Technical%20Resources/Bookstore/ASHRAE_TC0909_Power_White_Paper_22_June_2016_REVISED.pdf (visited on 04/18/2024).

[36] Google. *Efficiency - Data Centers - Google*. URL: https://www.google.com/about/datacenters/efficiency/ (visited on 02/24/2024).

[37] Gemma A. Brady et al. "A case study and critical assessment in calculating power usage effectiveness for a data centre". In: *Energy Conversion and Management* 76 (2013), pp. 155–161. ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2013.07.035. URL: https://www.sciencedirect.com/science/article/pii/S0196890413004068.

[38] Nathaniel Horner and Inês Azevedo. "Power usage effectiveness in data centers: overloaded and underachieving". In: *The Electricity Journal* 29.4 (2016), pp. 61–69. ISSN: 1040-6190. DOI: https://doi.org/10.1016/j.tej.2016.04.011. URL: https://www.sciencedirect.com/science/article/pii/S1040619016300446.

[39] Upsite Technologies Uptime Institute. *What is the average annual power usage effectiveness (PUE) for your largest data center?* 2023. URL: https://www.statista.com/statistics/1229367/data-center-average-annual-pue-worldwide/ (visited on 04/12/2024).

[40] Christian Belady Jack Pouchet Michael Patterson Dan Azevedo. *WATER USAGE EFFECTIVENESS (WUE): A GREEN GRID DATA CENTER SUSTAINABILITY METRIC*. White Paper 35. 2011. URL: https://www.thegreengrid.org/en/resources/library-and-tools/238-WP (visited on 07/10/2024).

[41] U.S. Environmental Protection Agency. *Water Efficiency Management Guide Mechanical Systems*. 2017. URL: https://www.epa.gov/sites/default/files/2017-12/documents/ws-commercialbuildings-waterscore-mechanical-systems-guide.pdf (visited on 07/08/2024).

[42] Google. *Restoring Ecosystems though Water Stewardship - Google Sustainability*. URL: https://sustainability.google/operating-sustainably/water-stewardship/ (visited on 07/10/2024).

[43] Bengt Sundén. "Chapter 3 - Hydrogen". In: *Hydrogen, Batteries and Fuel Cells*. Ed. by Bengt Sundén. Academic Press, 2019, pp. 37–55. ISBN: 978-0-12-816950-6. DOI: https://doi.org/10.1016/B978-0-12-816950-6.00003-8. URL: https://www.sciencedirect.com/science/article/pii/B9780128169506000038.

[44] McKinsey & Company The Hydrogen Council. *Hydrogen Insights 2023, The state of the global hydrogen economy, with a deep dive into renewable hydrogen cost evolution*. Tech. rep. 2023. URL: https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf (visited on 02/09/2024).

[45] Stanwell. *True colours: What do the different colours of hydrogen mean?* URL: https://whatswatt.com.au/true-colours-what-do-the-different-colours-of-hydrogen-mean/ (visited on 07/04/2024).

[46] Muhammad Younas et al. "An Overview of Hydrogen Production: Current Status, Potential, and Challenges". In: *Fuel* 316 (2022), p. 123317. ISSN: 0016-2361. DOI: https://doi.org/10.1016/j.fuel.2022.123317. URL: https://www.sciencedirect.com/science/article/pii/S0016236122001867.

[47] "Liquid Hydrogen: A Review on Liquefaction, Storage, Transportation, and Safety". In: *Energies* 14.18 (). DOI: 10.3390/en14185917.

[48] Sam Hawkins and D Joffe. "Technological characterisation of hydrogen storage and distribution technologies". In: *Policy Studies Institute: London, UK* (2006). URL: https://www.academia.edu/904707/Technological_characterisation_of_hydrogen_storage_and_distribution_technologies.

[49] Muhammad R. Usman. "Hydrogen storage methods: Review and current status". In: *Renewable and Sustainable Energy Reviews* 167 (2022), p. 112743. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2022.112743. URL: https://www.sciencedirect.com/science/article/pii/S1364032122006311.

[50] Office of Energy Efficiency & Renewable Energy U.S Department of Energy. *Hydrogen Delivery | Department of Energy*. URL: https://www.energy.gov/eere/fuelcells/hydrogen-delivery (visited on 04/10/2024).

[51] Mustafa Balat. "Potential importance of hydrogen as a future solution to environmental and transportation problems". In: *International Journal of Hydrogen Energy* 33.15 (2008), pp. 4013–4029. ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2008.05.047. URL: https://www.sciencedirect.com/science/article/pii/S0360319908005272.

[52] Bernard Chukwudi Tashie-Lewis and Somtochukwu Godfrey Nnabuife. "Hydrogen Production, Distribution, Storage and Power Conversion in a Hydrogen Economy - A Technology Review". In: *Chemical Engineering Journal Advances* 8 (2021), p. 100172. ISSN: 2666-8211. DOI: https://doi.org/10.1016/j.ceja.2021.100172. URL: https://www.sciencedirect.com/science/article/pii/S2666821121000880.

[53] Pasquale Cavaliere. "Hydrogen Infrastructure". In: *Water Electrolysis for Hydrogen Production*. Cham: Springer International Publishing, 2023, pp. 543–564. ISBN: 978-3-031-37780-8. DOI: 10.1007/978-3-031-37780-8_15. URL: https://doi.org/10.1007/978-3-031-37780-8_15.

[54] Pasquale Cavaliere. "Electrolysis Economy". In: *Water Electrolysis for Hydrogen Production*. Cham: Springer International Publishing, 2023, pp. 793–830. ISBN: 978-3-031-37780-8. DOI: 10.1007/978-3-031-37780-8_20. URL: https://doi.org/10.1007/978-3-031-37780-8_20.

[55] Office of Energy Efficiency & Renewable Energy U.S Department of Energy. *Hydrogen Delivery | Department of Energy*. URL: https://www.energy.gov/eere/fuelcells/hydrogen-pipelines (visited on 04/10/2024).

[56] European Association for the Streamlining of Energy Exchange. *Hydrogen Quality Specification*. 2021. URL: https://easee-gas.eu/download_file/DownloadFile/36/cbp-2022-001-01-hydrogen-quality-specification (visited on 02/26/2024).

[57] Furat Dawood, Martin Anda, and G.M. Shafiullah. "Hydrogen production for energy: An overview". In: *International Journal of Hydrogen Energy* 45.7 (2020), pp. 3847–3869. ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2019.12.059. URL: https://www.sciencedirect.com/science/article/pii/S0360319919345926.

[58] Taejun Kim et al. "A review of recent advances in hydrogen purification for selective removal of oxygen: Deoxo catalysts and reactor systems". In: *International Journal of Hydrogen Energy* 47.59 (2022), pp. 24817–24834. ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2022.05.221. URL: https://www.sciencedirect.com/science/article/pii/S0360319922023783.

[59] Duck-Kyu Oh, Kwan-Young Lee, and Jong-Soo Park. "Hydrogen Purification from Compact Palladium Membrane Module Using a Low Temperature Diffusion Bonding Technology". In: *Membranes* 10.11 (2020). ISSN: 2077-0375. DOI: 10.3390/membranes10110338. URL: https://www.mdpi.com/2077-0375/10/11/338.

[60] Xu Yang Chen et al. "A Review on the Metal Hydride Based Hydrogen Purification and Separation Technology". In: *Renewable Energy and Environmental Technology*. Vol. 448. Applied Mechanics and Materials. Trans Tech Publications Ltd, Jan. 2014, pp. 3027–3036. DOI: 10.4028/www.scientific.net/AMM.448-453.3027.

[61] Alexey Kazakov et al. "Metal hydride technologies for renewable energy". In: *E3S Web of Conferences*. Vol. 114. EDP Sciences. 2019, p. 05005. URL: https://www.e3s-conferences.org/articles/e3sconf/pdf/2019/40/e3sconf_esr2019_05005.pdf.

[62] Anna Król et al. "Hydrogen Purification Technologies in the Context of Its Utilization". In: *Energies* 17.15 (2024). ISSN: 1996-1073. DOI: 10.3390/en17153794. URL: https://www.mdpi.com/1996-1073/17/15/3794.

[63] Pasquale Cavaliere. "Hydrogen Separation and Purification". In: *Water Electrolysis for Hydrogen Production*. Cham: Springer International Publishing, 2023, pp. 509–541. ISBN: 978-3-031-37780-8. DOI: 10.1007/978-3-031-37780-8_14. URL: https://doi.org/10.1007/978-3-031-37780-8_14.

[64] Himadry Shekhar Das et al. "9 - Fuel cell and hydrogen power plants". In: *Hybrid Renewable Energy Systems and Microgrids*. Ed. by Ersan Kabalci. Academic Press, 2021, pp. 313–349. ISBN: 978-0-12-821724-5. DOI: https://doi.org/10.1016/B978-0-12-821724-5.00009-X. URL: https://www.sciencedirect.com/science/article/pii/B978012821724500009X.

[65] Jennifer Kurtz et al. "Analysis of hydrogen infrastructure for the feasibility, economics, and sustainability of a fuel cell powered data center". In: *Sustainable Energy Technologies and Assessments* 58 (2023), p. 103357. ISSN: 2213-1388. DOI: https://doi.org/10.1016/j.seta.2023.103357. URL: https://www.sciencedirect.com/science/article/pii/S2213138823003508.

[66] Omar Z. Sharaf and Mehmet F. Orhan. "An overview of fuel cell technology: Fundamentals and applications". In: *Renewable and Sustainable Energy Reviews* 32 (2014), pp. 810–853. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2014.01.012. URL: https://www.sciencedirect.com/science/article/pii/S1364032114000227.

[67] Yagmur Nalbant, C. Ozgur Colpan, and Yilser Devrim. "Energy and exergy performance assessments of a high temperature-proton exchange membrane fuel cell based integrated cogeneration system". In: *International Journal of Hydrogen Energy* 45.5 (2020). Hydrogen Energy Technologies for Mitigating Global Warming, pp. 3584–3594. ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2019.01.252. URL: https://www.sciencedirect.com/science/article/pii/S0360319919304367.

[68] Yılser Devrim, Ayhan Albostan, and Hüseyin Devrim. "Experimental investigation of CO tolerance in high temperature PEM fuel cells". In: *International Journal of Hydrogen Energy* 43.40 (2018). The 2nd International Symposium on Materials for Energy Storage and Conversion (mESC-IS2017), pp. 18672–18681. ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2018.05.085. URL: https://www.sciencedirect.com/science/article/pii/S036031991831601X.

[69] R. Kerr et al. "Lifetime and degradation of high temperature PEM membrane electrode assemblies". In: *International Journal of Hydrogen Energy* 40.46 (2015), pp. 16860–16866. ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2015.07.152. URL: https://www.sciencedirect.com/science/article/pii/S0360319915020972.

[70] S.J. Peighambardoust, S. Rowshanzamir, and M. Amjadi. "Review of the proton exchange membranes for fuel cell applications". In: *International Journal of Hydrogen Energy* 35.17 (2010), pp. 9349–9384. ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2010.05.017. URL: https://www.sciencedirect.com/science/article/pii/S0360319910009523.

[71] International Energy Agency. *The Future of Hydrogen - Siezing Today's Opportunities*. Tech. rep. 2019. URL: https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf.

[72] European Commission et al. *Global deployment of large capacity stationary fuel cells – Drivers of, and barriers to, stationary fuel cell deployment*. Publications Office, 2019. DOI: doi/10.2760/372263. URL: https://op.europa.eu/en/publication-detail/-/publication/d5b49b34-6a28-11e9-9f05-01aa75ed71a1/language-en.

[73] R.E. Rosli et al. "A review of high-temperature proton exchange membrane fuel cell (HT-PEMFC) system". In: *International Journal of Hydrogen Energy* 42.14 (2017). Special Issue on Sustainable Fuel Cell and Hydrogen Technologies: The 5th International Conference on Fuel Cell and Hydrogen Technology (ICFCHT 2015), 1-3 September 2015, Kuala Lumpur, Malaysia, pp. 9293–9314. ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2016.06.211. URL: https://www.sciencedirect.com/science/article/pii/S0360319915313069.

[74] Rasoul Nikbakhti et al. "Absorption cooling systems – Review of various techniques for energy performance enhancement". In: *Alexandria Engineering Journal* 59.2 (2020), pp. 707–738. ISSN: 1110-0168. DOI: https://doi.org/10.1016/j.aej.2020.01.036. URL: https://www.sciencedirect.com/science/article/pii/S1110016820300375.

[75] Pongsid Srikhirin, Satha Aphornratana, and Supachart Chungpaibulpatana. "A review of absorption refrigeration technologies". In: *Renewable and Sustainable Energy Reviews* 5.4 (2001), pp. 343–372. ISSN: 1364-0321. DOI: https://doi.org/10.1016/S1364-0321(01)00003-X. URL: https://www.sciencedirect.com/science/article/pii/S136403210100003X.

[76] Moe Thiri Zun et al. "Towards techno-economics of green hydrogen as a primary combustion fuel for recreational vehicle vapor absorption refrigeration system". In: *Sustainable Energy Technologies and Assessments* 56 (2023), p. 103007. DOI: 10.1016/j.seta.2022.103007.

[77] Ballard. *Fuel Cell Power for Marine Applications*. URL: https://www.ballard.com/docs/default-source/spec-sheets/fcwavetm-specification-sheet.pdf?sfvrsn=6e44dd80_16 (visited on 05/16/2024).

[78] Romero R.J. Pilatowsky I. et al. "Cogeneration Fuel Cells – Air Conditioning Systems". In: *Cogeneration Fuel Cell-Sorption Air Conditioning Systems*. London: Springer London, 2011, pp. 103–120. ISBN: 978-1-84996-028-1. DOI: 10.1007/978-1-84996-028-1_6. URL: https://doi.org/10.1007/978-1-84996-028-1_6.

[79] Khosrow Ebrahimi, Gerard F. Jones, and Amy S. Fleischer. "A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities". In: *Renewable and Sustainable Energy Reviews* 31 (2014), pp. 622–638. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2013.12.007. URL: https://www.sciencedirect.com/science/article/pii/S1364032113008216.

[80] Siemens. *Connecting data centers and district heating networks*. Tech. rep. 2023. URL: https://assets.new.siemens.com/siemens/assets/api/uuid:ddbf25c8-95c5-4843-861b-6361c4289e4a/DataCenterWhitePaperCustomerReferenceGrundfos.pdf (visited on 06/14/2024).

[81] S Giddey, F.T Ciacchi, and S.P.S Badwal. "Design, assembly and operation of polymer electrolyte membrane fuel cell stacks to 1 kWe capacity". In: *Journal of Power Sources* 125.2 (2004), pp. 155–165. ISSN: 0378-7753. DOI: https://doi.org/10.1016/j.jpowsour.2003.08.026. URL: https://www.sciencedirect.com/science/article/pii/S0378775303009248.

[82] Panasonic. *Panasonic Begins Demonstration Using Heat from Pure Hydrogen Fuel Cell Generators as a Heat Source for an Absorption Chiller*. 2024. URL: https://news.panasonic.com/global/press/en240729-2 (visited on 06/10/2024).

[83] U.S. Department of Energy. Office of Energy Efficiency & Renewable Energy. *Hydrogen and Fuel Cell Technologies Office Multi-Year Program Plan*. Tech. rep. 2023. URL: https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdf.

[84] Siôn Geschwindt. *Netherlands starts building €1.5B hydrogen pipeline to cut reliance on natural gas*. 2023. URL: https://thenextweb.com/news/netherlands-hydrogen-pipeline-natural-gas-energy (visited on 02/24/2024).

[85] Hynetwork. *Hydrogen Network 2030 and further*. 2024. URL: https://www.hynetwork.nl/en/about-hynetwork/hydrogen-network-netherlands (visited on 03/26/2024).

[86] Gasunie. *Hydrogen Pipeline in Zeeland Has Been Proving Added Value for Three Years*. https://www.gasunie.nl/en/news pipeline-in-zeeland-has-been-proving-added-value-for-three-years. 2021. (Visited on 02/28/2024).

[87] Air Products. *Air Products' U.S. Gulf Coast hudrogen network*. Tech. rep. 2012. URL: https://microsites.airproducts.com/h2-pipeline/pdf/air-products-us-gulf-coast-hydrogen-network-datasheet.pdf.

[88] Hynetwork. *Indicative quality and temperature specification for Hydrogen Network Netherlands*. 2024. URL: https://www.hynetwork.nl/uploads/fckconnector/42646914-a194-5cad-a9c0-5ab6207ea982 (visited on 02/26/2024).

[89] Ministerie van Economische Zaken en Klimaat. *Kwaliteitseisen voor waterstof t.b.v. het transportnet*. 2022. URL: https://open.overheid.nl/documenten/ronl-385383e0a0db4e2db9f6c1688273f9fefa0c4857/pdf (visited on 02/26/2024).

[90] Viviana Cigolotti, Matteo Genovese, and Petronilla Fragiacomo. "Comprehensive Review on Fuel Cell Technology for Stationary Applications as Sustainable and Efficient Poly-Generation Energy Systems". In: *Energies* 14.16 (2021). ISSN: 1996-1073. DOI: 10.3390/en14164963. URL: https://www.mdpi.com/1996-1073/14/16/4963.

[91] Accelera. *Stationary Solutions Fuel Cell Power Systems*. 2024. URL: https://www.accelerazero.com/sites/default/files/2024-03/Final_FuelCellPowerSystems-SpecSheet_March24.pdf (visited on 05/16/2024).

[92] Plug Power. *Plug Megawatt Scale Fuel Cell Power Generation Brochure*. 2023. URL: https://resources.plugpower.com/product-literature/plug-megawatt-scale-fuel-cell-power-generation-brochure-north-america (visited on 05/16/2024).

[93] Nedstack. *PemGen CHP-FCPS-600*. 2024. URL: https://nedstack.com/sites/default/files/2023-04/chp-fcps-600_0.pdf (visited on 05/16/2024).

[94] Neophytides, Stylianos et al. "High Temperature PEM Fuel Cell Stacks with Advent TPS Meas". In: *E3S Web Conf.* 16 (2017), p. 10002. DOI: 10.1051/e3sconf/20171610002.

[95] Advent Technologies. *Advent Technologies Announces Availability of Next-Generation HT-PEM MEAs*. URL: https://advent.energy/2022/03/14/advent-technologies-announces-availability-of-next-generation-ht-pem-meas/ (visited on 06/23/2024).

[96] Blue World Technologies. *HT PEM fuel cell stack*. URL: https://www.blue.world/wp-content/uploads/2023/11/20231031_Stack_data-sheet_ENG-1.pdf (visited on 06/23/2024).

[97] Ballard. *Stationary Power Generation - Fuel Cell Power Products | Ballard*. URL: https://www.ballard.com/fuel-cell-solutions/fuel-cell-power-products/backup-power-systems (visited on 05/16/2024).

[98] Thermax. *Double Effect Steam Driven Absorption Chiller*. URL: https://absorptionchiller.com.au/wp-content/uploads/2022/08/S2-Double-Effect-Steam-Fired_International.pdf (visited on 05/03/2024).

[99] Tecochill. *Natural Gas Engine-Driven Chillers Water-Cooled STx / DTx Series*. URL: https://d1io3yog0oux5.cloudfront.net/_bc180942e4cabc6ae509b7727b131217/tecogen/db/271/848/pdf/STxDTx-DataSheet.pdf (visited on 05/06/2024).

[100] Inc. Yazaki Energy Systems. *Top Features of Yazaki Energy System Gas Fired Double-Effect Chiller-Heaters CH-MG Series Specifications*. URL: https://www.yazakienergy.com/gasfiredspecifications_chmg.htm (visited on 05/03/2024).

[101] York. *YHAU-CL/CH Single Effect Hot Water Absorption Chiller | YORK*. URL: https://www.york.com/commercial-equipment/chilled-water-systems/absorption-chillers/yhau_cl_ch_ch/yhau-cl-ch-single-effect-hot-water-absorption-chiller#resources (visited on 05/03/2024).

[102] Tokuyama Corporation Ebara Corpration Ebara Refrigeration Equipment & Systems Co. Ltd. *Agreement with Ebara Group Concerning Pilot Test of Hydrogen-Powered Absorption Chiller-Heater*. 2024. URL: https://www.tokuyama.co.jp/eng/news/2024/2024072201.html (visited on 07/03/2024).

[103] Hao Li et al. "Safety of hydrogen storage and transportation: An overview on mechanisms, techniques, and challenges". In: *Energy Reports* 8 (2022), pp. 6258–6269. ISSN: 2352-4847. DOI: https://doi.org/10.1016/j.egyr.2022.04.067. URL: https://www.sciencedirect.com/science/article/pii/S2352484722008332.

[104] Pasquale Cavaliere. "Safety Issues and Regulations". In: *Water Electrolysis for Hydrogen Production*. Cham: Springer International Publishing, 2023, pp. 729–791. ISBN: 978-3-031-37780-8. DOI: 10.1007/978-3-031-37780-8_19. URL: https://doi.org/10.1007/978-3-031-37780-8_19.

[105] Buttner W.J.1 Pearman D.E.1 Hartmann K. 1 Post M.B.1 and I. Palin. *THE NREL SENSOR LABORATORY: HYDROGEN LEAK DETECTION FOR LARGE SCALE DEPLOYMENTS*. 2024. URL: https://www.nrel.gov/docs/fy24osti/85816.pdf (visited on 08/04/2024).

[106] Seyed Ehsan Hosseini. "Chapter 1 - Hydrogen, a green energy carrier". In: *Fundamentals of Hydrogen Production and Utilization in Fuel Cell Systems*. Ed. by Seyed Ehsan Hosseini. Elsevier, 2023, pp. 1–37. ISBN: 978-0-323-88671-0. DOI: https://doi.org/10.1016/B978-0-323-88671-0.00004-8. URL: https://www.sciencedirect.com/science/article/pii/B9780323886710000048.

[107] Dicks Andrew Larminie James. *A1.1 Hydrogen Fuel Cell*. 2003. URL: https://app.knovel.com/hotlink/khtml/id:kt00305VJ2/fuel-cell-systems-explained/hydrogen-fuel-cell.

[108] Qinghe Li et al. "A Review on Temperature Control of Proton Exchange Membrane Fuel Cells". In: *Processes* 9.2 (2021). ISSN: 2227-9717. DOI: 10.3390/pr9020235. URL: https://www.mdpi.com/2227-9717/9/2/235.

[109] Caesar Wu and Rajkumar Buyya. "Chapter 14 - Cost Modeling: Terms and Definitions". In: *Cloud Data Centers and Cost Modeling*. Ed. by Caesar Wu and Rajkumar Buyya. Morgan Kaufmann, 2015, pp. 579–609. ISBN: 978-0-12-801413-4. DOI: https://doi.org/10.1016/B978-0-12-801413-4.00014-3. URL: https://www.sciencedirect.com/science/article/pii/B9780128014134000143.

[110] Neil Rasmussen. *Determining Total Cost of Ownership for Data Center and Network Room Infrastructure*. White Paper 6. 2012. URL: http://www.apc.com/wp?wp=6.

[111] Mohamed H.S. Bargal et al. "Liquid cooling techniques in proton exchange membrane fuel cell stacks: A detailed survey". In: *Alexandria Engineering Journal* 59.2 (2020), pp. 635–655. ISSN: 1110-0168. DOI: https://doi.org/10.1016/j.aej.2020.02.005. URL: https://www.sciencedirect.com/science/article/pii/S1110016820300600.

[112] Akhilesh Arora and S. C. Kaushik. "Theoretical analysis of LiBr/H2O absorption refrigeration systems". In: *International Journal of Energy Research* 33.15 (2009), pp. 1321–1340. DOI: https://doi.org/10.1002/er.1542. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/er.1542. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/er.1542.

[113] R. Maryami and A.A. Dehghan. "An exergy based comparative study between LiBr/water absorption refrigeration systems from half effect to triple effect". In: *Applied Thermal Engineering* 124 (2017), pp. 103–123. ISSN: 1359-4311. DOI: https://doi.org/10.1016/j.applthermaleng.2017.05.174. URL: https://www.sciencedirect.com/science/article/pii/S1359431117304118.

[114] Rabah Gomri. "Second law comparison of single effect and double effect vapour absorption refrigeration systems". In: *Energy Conversion and Management* 50.5 (2009), pp. 1279–1287. ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2009.01.019. URL: https://www.sciencedirect.com/science/article/pii/S0196890409000272.

[115] L. Garousi Farshi et al. "A comparative study of the performance characteristics of double-effect absorption refrigeration systems". In: *International Journal of Energy Research* 36.2 (2012), pp. 182–192. DOI: https://doi.org/10.1002/er.1791. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/er.1791. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/er.1791.

[116] L.A. Domínguez-Inzunza et al. "Comparison of the Performance of Single Effect, Half Effect, Double Effect in Series and Inverse Absorption Cooling Systems Operating with the Mixture H2O-LiBr". In: *Energy Procedia* 57 (2014). 2013 ISES Solar World Congress, pp. 2534–2543. ISSN: 1876-6102. DOI: https://doi.org/10.1016/j.egypro.2014.10.264. URL: https://www.sciencedirect.com/science/article/pii/S1876610214016312.

[117] Muhammad Saad Khan et al. "A new correlation for performance prediction of small and large capacity single-effect vapor absorption refrigeration systems". In: *Cleaner Energy Systems* 1 (2022), p. 100002. ISSN: 2772-7831. DOI: https://doi.org/10.1016/j.cles.2022.100002. URL: https://www.sciencedirect.com/science/article/pii/S2772783122000012.

[118] Uptime Institute. *A Simple Model for Determining True Total Cost of Ownership for Data Centers*. White Paper. 2007. URL: https://datacenters.lbl.gov/sites/default/files/%28TUI3011B%29SimpleModelDetermingTrueTCO.pdf (visited on 03/03/2024).

[119] Caesar Wu and Rajkumar Buyya. “Chapter 17 - Cost Model Calculation”. In: *Cloud Data Centers and Cost Modeling*. Ed. by Caesar Wu and Rajkumar Buyya. Morgan Kaufmann, 2015, pp. 675–705. ISBN: 978-0-12-801413-4. DOI: https://doi.org/10.1016/B978-0-12-801413-4.00017-9. URL: https://www.sciencedirect.com/science/article/pii/B9780128014134000179.

[120] Ahmad Mayyas Shuk Han Chan David Gosselin Hanna Breunig Thomas McKone Max Wei Timothy Lipman. *A Total Cost of Ownership Model for High Temperature PEM Fuel Cells in Combined Heat and Power Applications*. Tech. rep. 2014. URL: https://www.energy.gov/eere/fuelcells/articles/total-cost-ownership-model-high-temperature-pem-fuel-cells-combined-heat (visited on 07/20/2024).

[121] U.S. Department of Energy. Office of Energy Efficiency & Renewable Energy. *Combined Heat and Power Technology Fact Sheet Series*. Tech. rep. URL: https://www.energy.gov/sites/default/files/2017/06/f35/CHP-Absorption%20Chiller-compliant.pdf.

[122] DC1. *Amsterdam region data centers power rates announced*. 2022. URL: https://dc1.amsterdam/en/blog/amsterdam-region-data-centers-power-rates-announced/ (visited on 08/10/2024).

[123] Overstappen. *Stroomprijs 2024 | Bekijk de kWh prijs van 19 leveranciers*. 2024. URL: https://www.overstappen.nl/energie/stroomprijs/ (visited on 08/10/2024).