Developing a Novel and Integrated Datacenter Concept Design Based on Hydrogen Production

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Abstract

Over the past few decades, data centers have made significant strides in enhancing their sustainability practices. These efforts range from minimizing power usage effectiveness (PUE) and carbon usage effectiveness (CUE) to enhancing water usage effectiveness (WUE). However, it's time for the data center industry to take a groundbreaking step forward. By effectively managing waste heat, data centers can become energy providers, boosting their profitability, and improving their energy reuse effectiveness (ERE) metrics. In this paper, we explore the crucial role of efficient heat management in optimizing the performance of an electrolyzer and maximizing the production of green hydrogen. Specifically, we focus on the importance of maintaining the stack temperature of the electrolyzer within a specific range to ensure maximum efficiency. We then propose a novel and integrated design concept for data centers that combines hydrogen production with district heating. An electrolyzer can be connected to both the data center and district heating systems, enabling the heat management system of the data center (e.g., heat pump) for powering the electrolyzer. Additionally, district heating can be utilized for thermal management of the electrolyzer, further improving the overall efficiency of the system. Additionally, the waste heat produced during the electrolysis process can be harnessed and employed to supplement the district heating system. This symbiotic relationship between the two systems results in a reduction in carbon emissions and improved energy efficiency. Our paper examines the technical feasibility of this proposed system and highlights the potential benefits for data centers and district heating systems.

Keywords:

Datacenter; Hydrogen production; Waste heat recovery; District heating; Green transition

1. Introduction

Data centers are essential for the modern digital economy, enabling the storage, processing, and transmission of vast amounts of data [1]. However, data centers have become a significant contributor to global energy consumption and carbon emissions, which has led to a growing focus on sustainability in the industry [2]. In recent years, data centers have made significant strides in improving their energy and water usage effectiveness, but there is still untapped potential for waste heat recovery to generate energy and improve their environmental metrics [3]. The energy consumption of data centers (DCs) has significantly expanded in response to the expansion of the information technology industry, which in 2019 used around 3% of the world's electricity supply [4]. The consumption is growing at a pace of 15-20% annually [5]. The electricity needed to run cooling systems accounts for around 40% of the power utilized by DCs [6]. On the one hand, the usage of high-grade electrical energy to fulfill the low-grade cooling DC requirements results in a considerable energy loss of energy flow in DCs [7]. On the other hand, the electric refrigeration systems in DCs often discharge a significant quantity of waste heat to the external environment, which results in urban heat islands [8]. Therefore, it is necessary to enhance the DC energy systems' structure and thermodynamic energy efficiency. If significant quantities of low- and medium-grade waste heat could be efficiently recovered and used for things like building heating, water heating, and refrigeration, DCs may be regarded as energy producers [9]. As a result, data centers (DCs) could fully embrace the concept of prosumers, who simultaneously act as producers and consumers, and surpass the current energy efficiency optimization model, which only considers the consumer perspective. Apart from utilizing waste heat across the system, a DC energy system can be tailored

https://doi.org/10.52202/069564-0083

to the overall energy system, an integrated energy system, or a systematic approach to the energy network. With the expected growth in demand for data-based services and the accompanying power consumption, data centers are seeking cost-effective, sustainable, and dependable ways to power their operations. Hydrogen and fuel cells are viable options that could fulfill these requirements and integrate with a variety of potential benefits.

What is the need for a new design in data centers? There are multiple factors that could drive a departure from the conventional data center design. Data centers have significant power and space requirements, which necessitate considering regional factors such as land and labor costs, access to affordable power, and business-friendly governmental policies when selecting their locations. Stricter air permitting regulations for diesel backup generators in certain regions could reinforce the case for integrating hydrogen and fuel cells. Furthermore, some companies have established corporate strategies to increase their reliance on non-carbon or green fuels, with a few already transitioning to 100% renewables and other co-locators following suit. This provides further rationale for using green hydrogen or locating data centers near wind or other renewable power sources [10].

The literature on sustainable data centers has focused on reducing energy and water consumption, improving energy efficiency, and exploring renewable energy sources. Grange et al. [11] developed an algorithm for scheduling the data center by renewable energy. Their results showed a reduction of brown energy consumption up to 49%. According to Khosravi et al. [12], an ejector heat pump was designed to recover waste heat from a data center for use in a low temperature district heating network in Finland. The study revealed that the use of a water-water heat pump is a viable method for recovering waste heat from data centers. Iverson et al. [13] focused on the design of hybrid renewable energy systems (HRES) for data center applications, leveraging hydrogen storage technology. The aim of their research was to develop an optimal design for HRES that would effectively meet the energy demands of data centers, while minimizing energy costs and reducing the environmental impact of the system.

While these studies provide valuable insights into the potential for waste heat recovery in data centers, there is a need for more research on the specific technical and economic aspects of integrating hydrogen generation into data center infrastructure. This paper aims to contribute to this literature by proposing a novel and integrated data center concept design based on hydrogen production and conducting an analysis to determine its feasibility and potential. This paper proposes a novel approach to data center sustainability, in which waste heat is captured and reused to generate hydrogen fuel. By integrating an electrolyzer into the data center infrastructure, waste heat can be converted into a valuable energy source that can be used for district heating or as an ancillary service. This approach not only increases the overall profitability of data centers but also improves their environmental metrics by enhancing their energy reuse effectiveness. The proposed approach has the potential to transform the data center industry by making waste heat recovery a viable and profitable solution to energy generation. The approach not only improves the sustainability of data centers but also positions them as energy suppliers, which could have far-reaching implications for the broader energy industry. Overall, this paper contributes to the ongoing conversation on data center sustainability by proposing a novel and integrated design that has the potential to enhance both the environmental and economic performance of data centers.

2. Case study

Data centers are characterized by their use of air cooling, the most widely used technique in the sector, to provide low temperature, high capacity, and reliable heat. About 40% of the power utilized by DCs goes to power cooling systems. However, the electric refrigeration systems in DCs often release a significant amount of waste heat into the environment. The current Danfoss design for the data center at Nordborg is depicted in Figure 1. This system uses air cooled system to cool the data center. Danfoss is seeking for an alternate system because the current system is no longer providing economic benefits.

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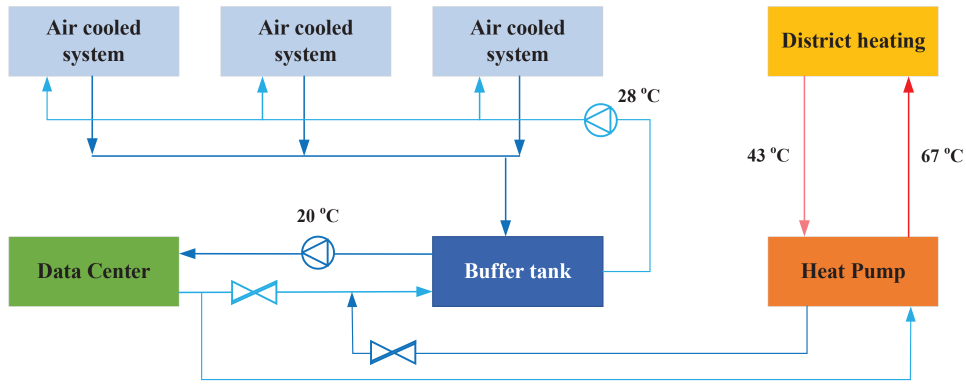

Figure 1. *Danfoss Nordborg data center, the current design.*

3. Material and methods

3.1 The proposed system

The system proposed in this paper incorporates an alkaline electrolyzer into a district heating system, heat pump layout, and data center, with the goal of optimizing the efficiency and sustainability of energy production. As shown in Figure 2, temperature control is a crucial factor in achieving optimal performance of the electrolyzer. To achieve this, the fourth generation of district heating networks is proposed for use with this technology, with the possibility of using the district heating for heat management of the electrolyzer. The heat pump is also an essential component for providing cooling for the data center and can be utilized for heat management of the electrolyzer. The heat pump has an electricity input of 174 kW and is capable of generating 824 kW of heat output and 650 kW of cooling output. The alkaline electrolyzer has a capacity of 2 MWe and produces 16.3 kg/h of hydrogen.

The system is powered by electricity from the NordPool electricity spot market, which is used to meet the electricity demand of the data center, which is 10,932,821 kWh as well as electricity demand for heat pump and electrolyzer. Additionally, the cooling demand of the data center is 3,000,000 kWh. To manage the thermal energy generated by the system, heat storage with a capacity of 6952 kWh and cooling storage with a capacity of 1158 kWh are included in the system design.

Furthermore, the electrolyzer is connected to the district heating network, allowing for the waste heat produced during the electrolysis process to be harnessed and employed to supplement the district heating system. The district heating system can be utilized as a free source for heat management of the electrolyzer. The system model proposed in this paper consists of an electrochemical model, a thermal model, and a model of the cooling system. The electrochemical model simulates the relationship between current and voltage for various operating temperatures and pressures, describing the kinetics of the reactions that take place and providing details required for precisely modeling the creation of heat inside the alkaline electrolyzer. The system proposed in this paper provides valuable insights into the potential for integrated energy systems to improve the sustainability and efficiency of energy production. Further research and development in this area may lead to the widespread implementation of similar systems, resulting in significant improvements in sustainability and energy efficiency.

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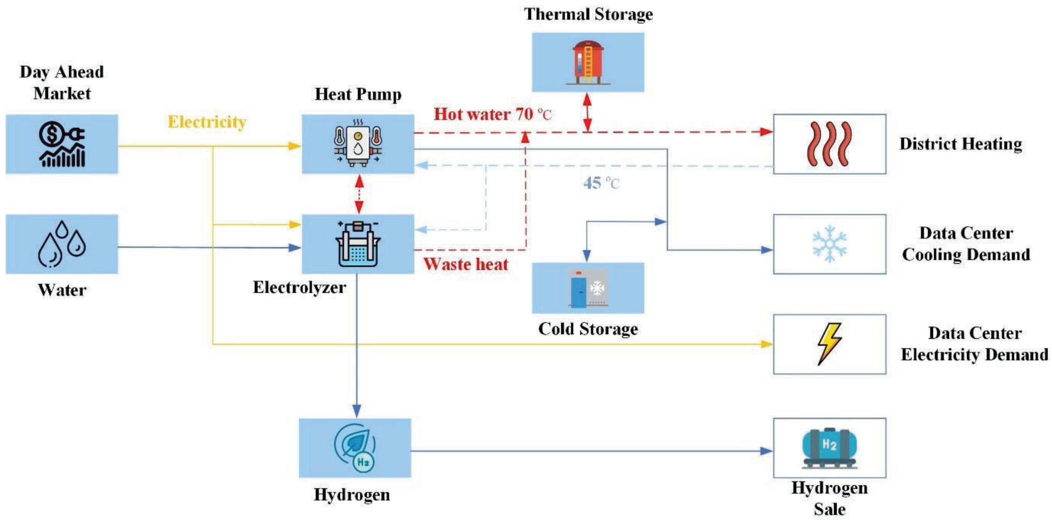

Figure 2. *Data center incorporated with alkaline electrolyzer.*

3.2 Electrolyzer Model

The following is a description of a mathematical model designed for a high-pressure alkaline water electrolyzer. The model is constructed by integrating fundamental principles of thermodynamics, heat transfer theory, and empirical electrochemical relationships. Additionally, the model includes a dynamic thermal component. The electrochemical model is based on a temperature dependent current-voltage curve at a specific pressure, as well as a Faraday efficiency relation that is not influenced by temperature or pressure.

The process of breaking down water into hydrogen and oxygen can be accomplished through the use of direct current (DC) passed between two electrodes that are separated by an aqueous electrolyte with strong ionic conductivity. The overall reaction for the separation of water can be expressed as:

$$H_2O(l) + \text{electrical energy} \rightarrow H_2(g) + \frac{1}{2} O_2(g) \tag{1}$$

For the reaction to take place, a minimum electric voltage must be applied to the two electrodes. This minimum voltage, also known as the reversible voltage, can be calculated using the Gibbs energy for water splitting. Alkaline electrolyzers typically use aqueous potassium hydroxide (KOH) as the electrolyte, with the potassium ion (K^+) and hydroxide ion (OH^-) facilitating ionic transport. The anodic and cathodic reactions that occur in this system can be described as follows:

$$\text{Anode: } 2OH^-(aq) \rightarrow \frac{1}{2} O_2(g) + H_2O(l) + 2e^- \tag{2}$$

$$\text{Cathode: } 2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq) \tag{3}$$

In an alkaline solution, the electrodes must possess properties such as resistance to corrosion, good electrical conductivity, and catalytic activity, as well as structural integrity, while the diaphragm should have low electrical resistance. This can be achieved by using anodes made of materials such as nickel, cobalt, and iron (Ni, Co, Fe), cathodes with a platinum-activated carbon catalyst on a nickel base (Ni, C-Pt), and diaphragms made of nickel oxide (NiO).

3.2.1 Thermodynamic Model

Thermodynamics serves as a framework to describe reaction equilibrium and thermal effects in electrochemical reactors and provides a basis for defining driving forces for transport phenomena in electrolytes. Additionally, it aids in describing the properties of electrolyte solutions. The thermodynamics of the low-temperature hydrogen-oxygen electrochemical reactions utilized in the electrolyzer model are described below.

Assumptions can be made about the water splitting reaction: (a) hydrogen and oxygen are ideal gases, (b) water is an incompressible fluid, and (c) the gas and liquid phases are separate. Based on these assumptions, changes in enthalpy (ΔH), entropy (ΔS), and Gibbs energy (ΔG) of the water splitting reaction can be calculated with respect to pure hydrogen (H_2), oxygen (O_2), and water (H_2O) at standard temperature and pressure (25°C

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and 1 bar). The total change in enthalpy for water splitting is the enthalpy difference between the products (H_2 and O_2) and the reactants (H_2O), and the same applies for the total change in entropy. The expression for the change in Gibbs energy is as follows [14]:

$$\Delta G = \Delta H - T\Delta S \tag{4}$$

In electrochemical processes, the splitting of water requires a significant amount of energy due to its positive change in Gibbs energy. At standard conditions (25°C and 1 bar), the standard Gibbs energy for water splitting is 237 kJ/mol, indicating that the reaction is non-spontaneous. However, Faraday's law states that the electrical energy required to split water is directly proportional to the chemical conversion rate in molar quantities. Therefore, the reversible cell voltage or *emf* for a reversible electrochemical process can be calculated using the change in Gibbs energy. This information is crucial when designing and optimizing electrochemical processes for the production of hydrogen and oxygen from water. The reversible cell voltage, also known as the electromotive force (*emf*) of a reversible electrochemical process, can be expressed as:

$$U_{rev} = \frac{\Delta G}{zF} \tag{5}$$

The expression relating the thermoneutral cell voltage to the total energy demand (ΔH) is:

$$U_{tn} = \frac{\Delta H}{zF} \tag{6}$$

3.2.2 Electrochemical model

Empirical current-voltage (I-U) relationships can be utilized to model the electrode kinetics of an electrolyzer cell. There are multiple suggested empirical I-U models for electrolyzers. In this study, the I-U curve utilized has a fundamental form that is dependent on the temperature, and can be expressed as:

$$U = U_{rev} + \frac{r}{A}I + s\ log\left(\frac{t}{A}I + 1\right) \tag{7}$$

The Faraday efficiency, also known as the current efficiency, is the ratio between the actual and theoretical maximum amount of hydrogen produced in an electrolyzer. The efficiency is affected by parasitic current losses along the gas ducts, which increase with decreasing current densities due to an increasing share of electrolyte and lower electrical resistance. The parasitic current is linearly proportional to the cell potential, which means that the fraction of parasitic currents to total current increases with decreasing current densities. An increase in temperature results in lower resistance, higher parasitic current losses, and lower Faraday efficiencies. Understanding the Faraday efficiency is essential for optimizing the performance and efficiency of an electrolyzer.

$$\eta_F = \frac{(I/A)^2}{f_1 + (I/A)^2} f_2 \tag{8}$$

Faraday's law states that the production rate of hydrogen in an electrolyzer cell is directly proportional to the transfer rate of electrons at the electrodes, which is equivalent to the electrical current flowing through the external circuit. Therefore, the total rate of hydrogen production in an electrolyzer, which comprises multiple cells connected in series, can be mathematically represented as:

$$\dot{n}_{H_2} = \eta_F \frac{n_c I}{zF} \tag{9}$$

The rate of oxygen production can be determined straightforwardly using stoichiometry, as shown in Eq. 11, which is expressed on a molar basis as:

$$\dot{n}_{H_2O} = \dot{n}_{H_2} = 2\dot{n}_{O_2} \tag{10}$$

The primary source of heat generation in an electrolyzer is attributed to electrical inefficiencies. The efficiency of energy conversion can be determined by utilizing the thermoneutral voltage (Equation 3) and the cell voltage (Equation 4), and is expressed mathematically as:

$$\eta_e = \frac{U_{tn}}{U} \tag{11}$$

3.2.3 Thermal Model

To determine the temperature of the electrolyte in an electrolyzer, a simple or complex thermal model can be employed depending on the required level of accuracy. If a lumped thermal capacitance model is assumed, the overall thermal energy balance can be expressed as a linear, non-homogeneous, first-order differential equation. This model enables the calculation of the stack temperature and analytically solves for the temperature distribution [14]:

$$C_t \frac{dT}{dt} = \dot{Q}_{gen} - \dot{Q}_{loss} - \dot{Q}_{cool} \quad (12)$$

$$\dot{Q}_{gen} = \eta_c(U - U_{tn})I = n_c U I(1 - \eta_e) \quad (13)$$

$$\dot{Q}_{cool} = C_{cw}\left(T_{cw,i} - T_{cw,o}\right) = UA_{HX} LMTD \quad (14)$$

4. Results and Discussion

The figure presented in this section, Figure 3, depicts the behavior of the cell voltage (V) of an alkaline electrolyzer as a function of current density (mA/cm^2). The results demonstrate that as the current density is increased, the cell voltage also increases, starting from 0 and reaching 1.88 V. Interestingly, after a current density of 300 (mA/cm^2), the cell voltage becomes nearly constant and remains horizontal. This suggests that the performance of the electrolyzer plateaus at higher current densities and that further increases in current density may not result in a significant improvement in performance. This finding is significant because it indicates the importance of careful selection of current density to achieve optimal performance of the electrolyzer for hydrogen production. By identifying the point of plateau in cell voltage, it is possible to determine the maximum current density that can be used for efficient and sustainable hydrogen production. Overall, the results presented in Figure 2 provide valuable insights into the behavior of the cell voltage of an alkaline electrolyzer as a function of current density. These insights are important for optimizing the performance of the electrolyzer and achieving maximum efficiency in hydrogen production.

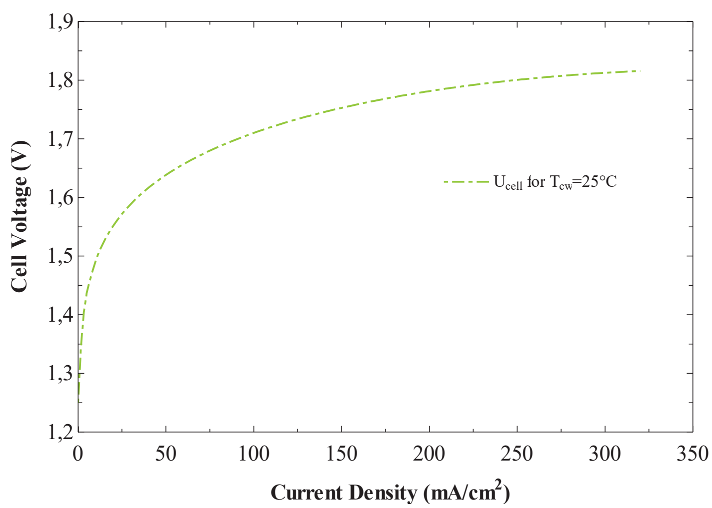

Figure 3. *Relationship between Cell Voltage and Current Density at 25℃ Cooling Water Temperature.*

Figure 4 presents the results of an investigation into the effects of current density and cooling water temperature on the temperature of an electrolyzer. The figure clearly shows that as the current density increases, the temperature of the electrolyzer also increases. Similarly, an increase in cooling water temperature results in a corresponding increase in the electrolyzer temperature. These findings highlight the importance of careful temperature management in optimizing the performance of the electrolyzer. If the electrolyzer temperature becomes too high, it can lead to reduced efficiency and potentially cause damage to the system. The results presented in Figure 4 have significant implications for the design and operation of electrolyzers. Specifically, they suggest that careful consideration must be given to the impact of both current density and cooling water temperature on the temperature of the electrolyzer. The analysis also shows that the use of district heating return water, which typically has a temperature of 43-45 ℃, could potentially be used

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to manage the temperature of the electrolyzer and maintain it at the desired value. Overall, the results presented in Figure 4 provide valuable insights into the factors that influence the performance of electrolyzers and offer guidance for their design and operation.

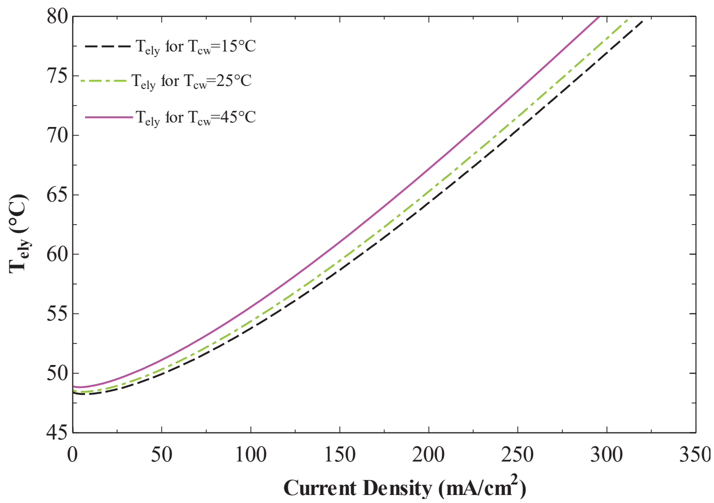

Figure 4. *Relationship between Current Density and Electrolyzer Temperature for Different Cooling Water Temperatures.*

Figure 5 illustrates the relationship between current density and the efficiency of hydrogen production in an alkaline electrolyzer. The figure indicates that as the current density increases from 0 to approximately 50 (mA/cm^2), the efficiency of hydrogen production increases from 0 to 80%. This finding highlights the potential for significant improvements in the efficiency of hydrogen production by increasing the current density. However, the results also show that beyond a current density of 50 (mA/cm^2), the efficiency of hydrogen production becomes almost constant, suggesting that further increases in current density may not result in a significant improvement in efficiency. These findings are significant for the optimization of electrolyzer performance in hydrogen production, as they emphasize the importance of carefully selecting the appropriate current density to achieve maximum efficiency. The results presented in Figure 5 offer valuable insights into the relationship between current density and the efficiency of hydrogen production in an alkaline electrolyzer and can inform the design and operation of electrolyzers for sustainable and efficient hydrogen production. Overall, Figure 5 provides important information for researchers and engineers working in the field of hydrogen production and underscores the potential for further advances in this critical area.

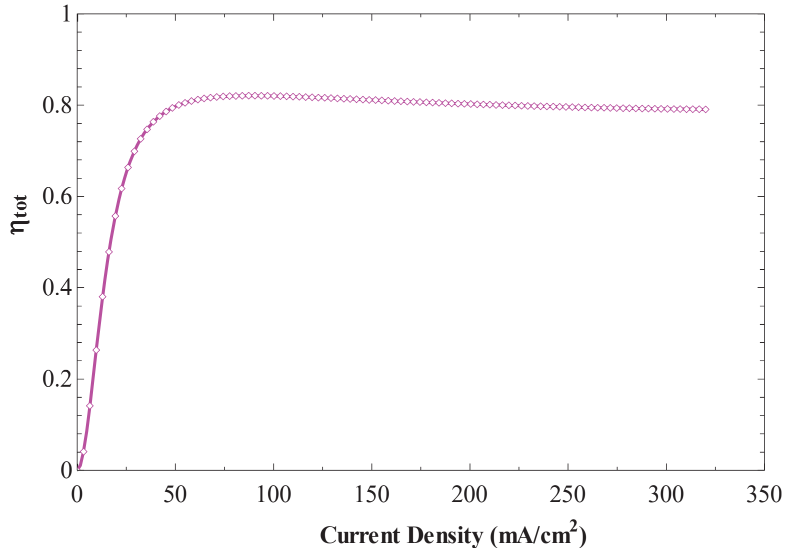

Figure 5. *Impact of Current Density on the Efficiency of Hydrogen Production.*

Figure 6 presents the results of an investigation into the impact of cooling temperature on the efficiency of hydrogen production in an electrolyzer (A), as well as its effect on electrolyzer temperature (B). The figure demonstrates that increasing the cooling temperature results in an increase in the efficiency of the electrolyzer, which in turn leads to an increase in the efficiency of hydrogen production. This finding is significant because it highlights the importance of careful temperature control for optimizing the performance of electrolyzers for hydrogen production. By maintaining an appropriate cooling temperature, it may be possible to improve the efficiency of the electrolyzer and increase the overall efficiency of hydrogen production. The results presented in Figure 6 provide valuable insights into the factors that influence the efficiency of hydrogen production in an electrolyzer and suggest that the use of district heating could potentially be used to manage the temperature of the electrolyzer and maintain it at an optimal value. In summary, the findings presented in Figure 6 demonstrate the importance of temperature control in the optimization of electrolyzer performance for hydrogen production.

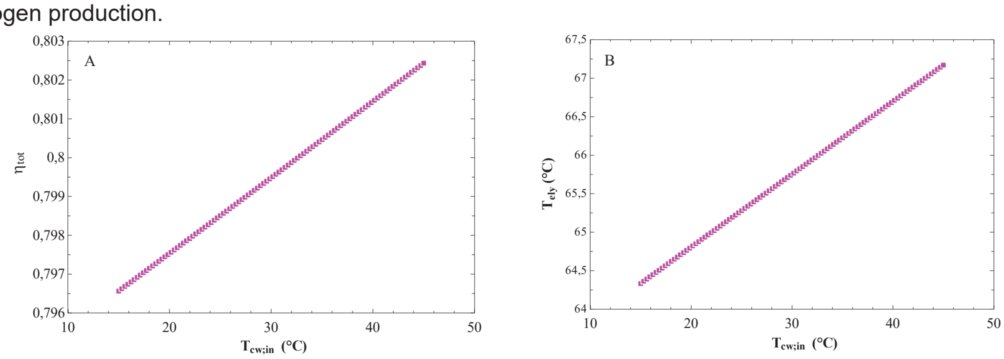

Figure 6. *(A) The effect of cooling water temperature over the efficiency of hydrogen production, (B) the effect of cooling water temperature over the electrolyzer temperature.*

Figure 7 presents an overview of the heat generation by a heat pump and electrolyzer, as well as the heat demand of a district heating system. The figure highlights that the demand for district heating in the summer months is significantly lower than in the winter months. This finding is important because it underscores the need to carefully consider the demand for waste heat when connecting an electrolyzer to a district heating network. In particular, it is crucial to ensure that there is sufficient demand for the waste heat generated by the electrolyzer in order to avoid potential inefficiencies or even system failures. The results presented in Figure 7 suggest that the design of the heat management system for an electrolyzer should consider the seasonal variation in district heating demand. If there is always sufficient district heating demand, then there may be no concerns about delivering the waste heat generated by the electrolyzer. However, if there is a significant

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imbalance between the heat generation and demand, then it may be necessary to explore other strategies for managing the waste heat, such as storage or alternative uses. Overall, Figure 7 provides important insights into the relationship between heat generation, demand, and waste heat management in the context of an electrolyzer connected to a district heating network. The results offer guidance for the design and operation of electrolyzers and can inform decision-making related to the integration of these systems with district heating networks. In this case the operation of electrolyzer is 73% and heat pump 90%.

Figure 8 illustrates the operation of thermal energy storage (TES) in the context of a district heating system. During periods of excess heat production, such as in the summer months when demand for district heating is low, the excess heat can be stored in the hot water tank. The TES system can then release the stored heat during periods of high demand.

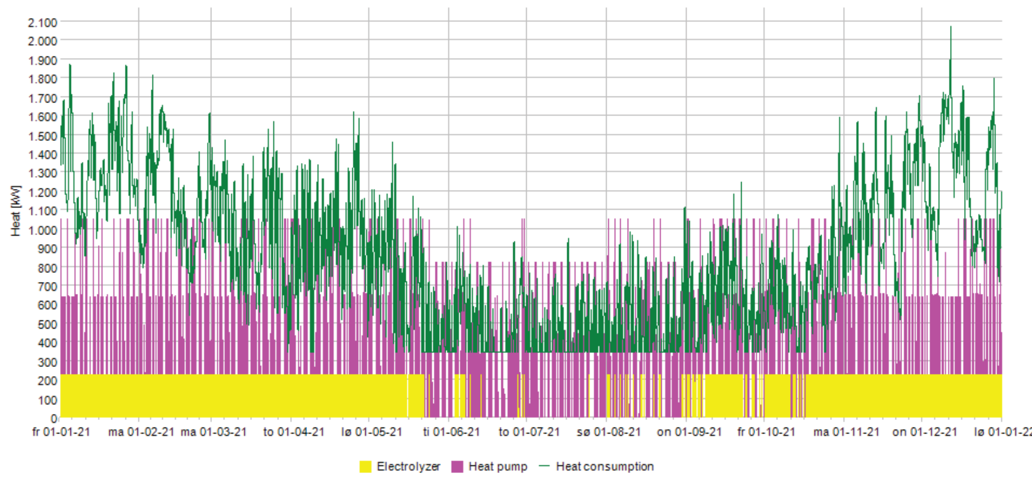

Figure 7. *Heat generation by heat pump and electrolyzer and heat demand of district heating.*

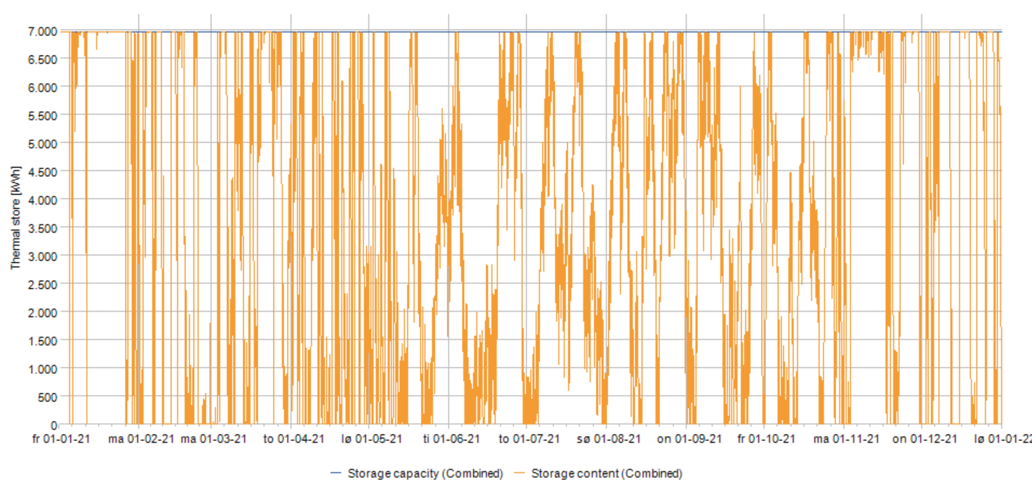

Figure 8. *The operation of thermal energy storage.*

Figure 9 presents the pattern of electricity consumption for a data center, heat pump, and electrolyzer over the course of one year. The figure provides valuable insights into the electricity consumption patterns of these systems and highlights the potential for optimization and efficiency improvements.

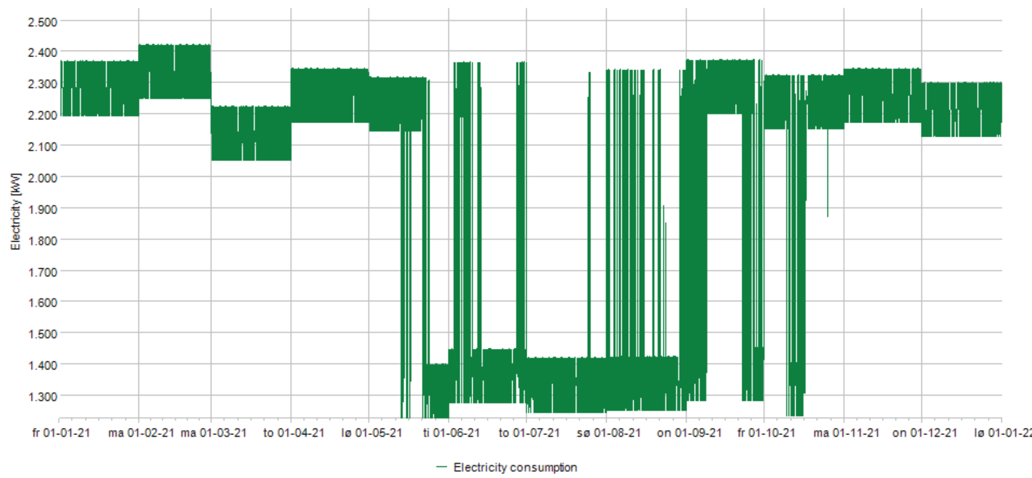

Figure 9*. Electricity consumption of heat pump, electrolyzer and data center.*

5. Conclusion

In conclusion, this paper has explored the crucial role of efficient heat management in optimizing the performance of alkaline electrolyzer and maximizing the production of green hydrogen. Specifically, the importance of current density and cooling temperature on the efficiency of the electrolyzer for hydrogen production has been demonstrated. The paper also proposed a novel and integrated design concept for data centers that combines hydrogen production with district heating, enabling waste heat to be harnessed and employed to supplement the district heating system. The results of this study showed that increasing the current density and cooling temperature can lead to significant improvements in the efficiency of hydrogen production, while careful temperature control is important for optimizing the performance of electrolyzers. Furthermore, by integrating hydrogen production with district heating, the waste heat produced during the electrolysis process can be harnessed and employed to supplement the district heating system, resulting in a reduction in carbon emissions and improved energy efficiency.

The technical and economic feasibility of the proposed system was examined, highlighting the potential benefits for data centers and district heating systems. The results suggest that the proposed system has the potential to improve the sustainability and efficiency of energy systems, contributing to the development of more environmentally friendly and economically viable solutions for energy production. Overall, this paper provides valuable insights into the future of sustainable energy systems and the potential for data centers to play a crucial role in this transition. Further research and development in this area may lead to the widespread implementation of integrated energy systems, resulting in significant improvements in sustainability and energy efficiency.

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