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Physics Concepts Based Data Centre Operations: A Medium for Education on Energy Efficiency and Technological Innovations

Stephen William Hughes[1,2*], Peter Schouten[2]

[1] School of Mathematics and Physics, University of Queensland, St. Lucia, Queensland 4072, Australia
[2] UQ College, University of Queensland, St. Lucia, Queensland 4072, Australia

**Corresponding Address: stephen.hughes@uq.edu.au*

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ABSTRACT

Data centres are considered the exclusive sites of information technology and computer science. However, many aspects of their day-to-day operation can be used to teach important concepts in physics, such as heat transfer, AC and DC power transmission, fibre optic transmission, energy loss in transmission cables, and electronic componentry. Data processing requirements and power usage in data centres are growing exponentially, and therefore, solutions need to be developed to reduce energy costs, given the challenges of global warming. To this end, work is being done on storing data in strands of DNA. An experiment to measure the change in temperature of air passing through an internet hub is described as a means of teaching students about the physics of data centres. The procedure and calculations shown in this particular experiment can be used and applied by secondary school physics students to evaluate the energy budget and efficiency of different data centres, such as those used at their school. In addition, this article details how students can make simple calculations that directly show how novel DNA data storage technology can be utilized to reduce the amount of hardware and power used at data centres. The potential for quantum computing to reduce the power requirements of data centres is also discussed.

INTRODUCTION

Data centres are now an integral part of the modern world. During their daily operations, they use systems and procedures that use physics concepts, such as heat transfer (and the laws of thermodynamics), DC and AC power transmission, fibre optics, energy loss in transmission cables, and electronic componentry. Consequently, discussing data centres in a physics class is a good way to connect many different modern and classical physics topics.

All students will be heavily using data centres via apps on their phones—for example, uploading photos and videos to social media platforms. Most students will also be aware of cloud storage and may have had to upgrade their service subscriptions to obtain access to more data storage. Recently, there has been an explosion in the use of artificial intelligence (AI) clients and applications, which is predicted to require an enormous amount of extra computing power and energy over the next few years (Stevens, 2023).

We have a proverbial 'perfect storm' – the combination of the requirement to reduce carbon emissions to limit the increase in the average global temperature and an upsurge in AI computing with prodigious energy requirements. Therefore, this is an important topic to teach physics students. It is also of vital interest to the general public.

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Data centres are now an integral part of the modern world. During their daily operations, data centres utilise systems and procedures that use physics concepts, such as heat transfer (and the laws of thermodynamics), DC and AC power transmission, fibre optics, energy loss in transmission cables, and electronic componentry. Studies on applying physics concepts in technological systems, such as energy efficiency in cooling systems and transmission losses in power systems (Apata et. al., 2021), provide foundational insights that can be extended to data centres. Additionally, research on integrating modern technological contexts into physics education, such as using renewable energy systems as teaching tools (Lee, 2021), highlights the importance of using real-world examples to enhance student engagement.

A review of the physics education literature did not discover any current papers overtly on the physics of data centres. This paper discusses the subject in the hope that it will be useful in teaching high school and undergraduate physics students.

This paper describes the results of an experiment to measure any change in the temperature of the air exiting the internet hub rack of a university data centre, providing a foundation for teaching students about energy and data centres.

University of Queensland Data Centre

The University of Queensland (UQ) data centre was established in 1964 and was the first in the southern hemisphere. In January 2023, the average power required to run the entire centre was 313.7 kW, distributed amongst three sub-data centres allocated to different tasks. Air conditioning accounts for 30% of the total energy cost. The total energy cost to run the UQ data centre in 2023 was 336,812 AUD (226,711 USD, 177,067 GBP) based on a price of 0.12 cents/kWh. (N.B. The University of Queensland obtains all electrical energy from a solar farm: https://sustainability.uq.edu.au/warwicksolarfarm). Figure 1 Shows the ICT and AC power for Data Centre 1 (DC1) for each month in 2023. An interesting observation is that the power required for air conditioning does not vary significantly between winter (June - August) and summer (December – March). This is probably because Brisbane winters are relatively warm.

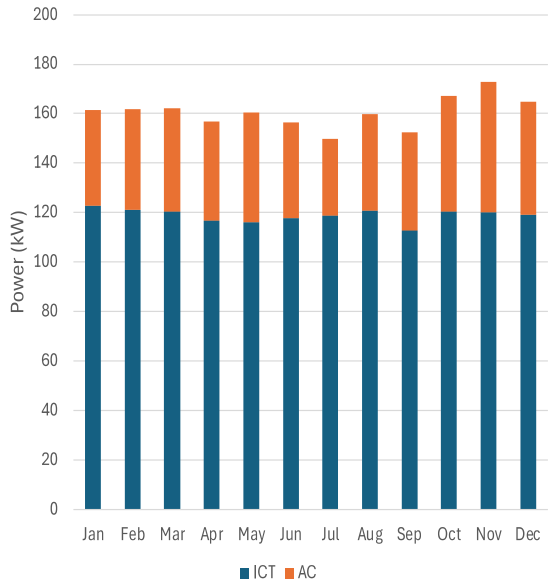

Figure 1. Average Power Used ICT and AC for DC1 in the UQ Data Centre for Each Month in 2023

Table 1 is a tabular version of the first column of Figure 1 and also provides data for the other two of the three data centres for January 2023.

Table 1. Power Consumption in kW of the Three Sections of the UQ Data Centre January 2023

	ICT	AC	Total
DC1	122.8	38.8	161.6
DC2	56.1	28.1	84.2
DC3	38.7	29.2	67.9
Total	217.6	96.1	313.7

Description:
ICT : Information and Communication Technologies
AC : Air conditioning
DC : Data Centre

When electrical power is provided to any device using wires, some energy is always lost in the wires. Cable power loss is governed by $P = I^2R$P being power, I is current, and R is the cable's resistance.

Long-range power lines reduce power loss by increasing the potential to hundreds of thousands of volts. This enables high power to be transmitted with a low current.

Data centres are relatively low-voltage devices that necessitate high currents, which increases cable power losses. For this reason, the UQ data centre is physically close to an on-campus substation. In the classroom, data centres can be cited as practical example$P = I^2R$s.

Cooling of the Internet Hub

Figure 2 shows the internet hub of the UQ data centre. The yellow strands are fibre optic cables. Note that the cables navigate tight bends, demonstrating that total internal reflection can transmit light around tight curves. Cold air emerges from floor vents below the hub, and fans at the rear of the rack draw the cold air through the electronics rack, taking away heat.

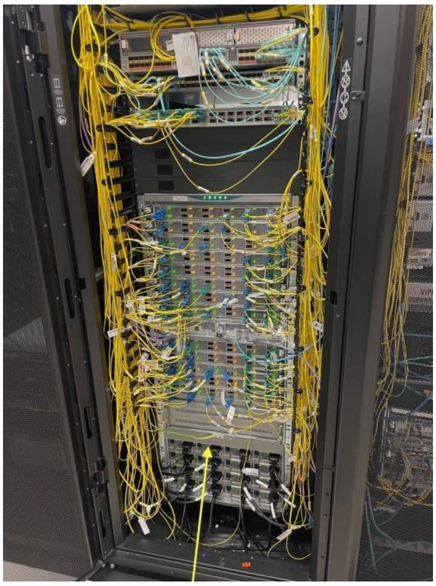

Figure 2. The Main Internet Hub of the UQ Data Centre. The Yellow Cables are Fibre Optic Cables. The Yellow Arrow Shows the Direction of the Flow of Cold Air from the Floor Vents

The temperature of equipment racks is controlled manually by opening and closing vents on the floor. There is no feedback control as such. Vents are open in front of racks under power and closed where racks are unpowered or empty.

METHODS

The Lexus Melbourne Cup is the peak horse race in the four-day Melbourne Cup Carnival, held each year on the first Tuesday of November at the Flemington Race Course in Melbourne, Victoria, Australia.

There is widespread interest in the race, with many viewers on TV and online attending in person. According to Thoroughbrednews (2023), the event was watched by 2.4 million in Australia in 2023, including 262 165 at the Flemington Race Course, 206 000 online, and the remainder on broadcast TV and cable. This is out of a total Australian population of 27 million. The event is approximately equivalent to the FA Cup in the UK and the Super Bowl in the US.

Temperature measurements were taken on 7 October 2023, just before and after the Lexus Melbourne Cup, to determine if there was any measurable increase in hub temperatures due to people logging on to the university servers to watch the race.

Figure 3 shows the vents on the rear of the internet hub being examined using the Fluke thermal imaging camera (Ti32), and Figure 4 shows an example of an image. Fluke SmartView Classic analysis software enables the temperature to be measured at a given point on the image.

A logging USB temperature probe (TempU 04 temperature logger (www.tzonedigital.com/en/default.aspx)) was positioned close to the cold air vent in the floor below the internet hub.

Another temperature probe was placed in the hub's outflow. In addition to the USB temperature sensor and the thermal imaging camera, a temperature probe (Digital Thermometer, Digitech) was attached to the rear of the hub rack. The temperature probes were positioned, and logging commenced about 15 minutes before 14:00 to allow time to equilibrate to the ambient temperature.

RESULTS AND DISCUSSION

The temperature measured by the Digitech probe remained steady at 39.6 ºC ($\pm$ 0.1) from 1:58 p.m. to 2:10 p.m. This further indicates that the hub cooling and air circulation system works efficiently during high data traffic/power loads.

Figure 5 displays the temperatures of the air entering and leaving the internet hub from 1:47 p.m. to 2:16 p.m., measured using the Temp U04 probes, which is the time interval when most university staff and students were logging in to watch the race.

It can be seen that from 14:00 to 14:15 when people logged in to see the race, which only lasted about 3 minutes and 20 seconds, there was little change in the temperature of the air entering and leaving the hub.

This indicates that the hub's cooling and air circulation system works efficiently under high data traffic/power load intervals. The data obtained by the thermal imaging camera corroborated the data collected by the USB temperature sensor, showing that temperatures only varied by approximately $\pm$ 2ºC throughout the duration of the 1:47 p.m. to 2:16 p.m. time interval over the external hub structure. This temperature variation is usually seen during daily data traffic/power load intervals.

Figure 3. Using the Thermal Imaging Camera to Measure the Temperature of the Rear of the Internet Hub. The Yellow Arrow Shows the Direction of the Air Flow

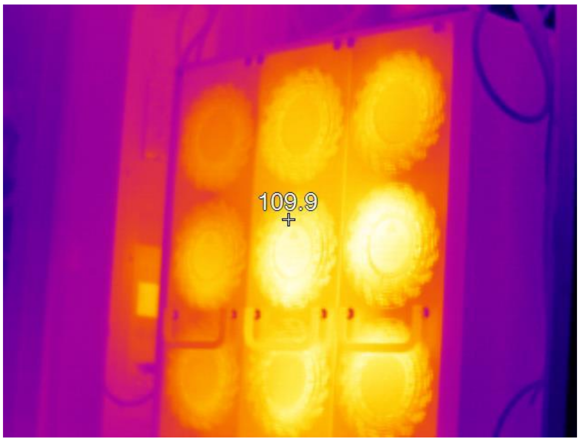

Figure 4. An Example Image Obtained from the Thermal Imaging Camera. The Temperature in Fahrenheit (109.9 °F = 43.3 °C) Is Shown at the Position of the Crosshairs.

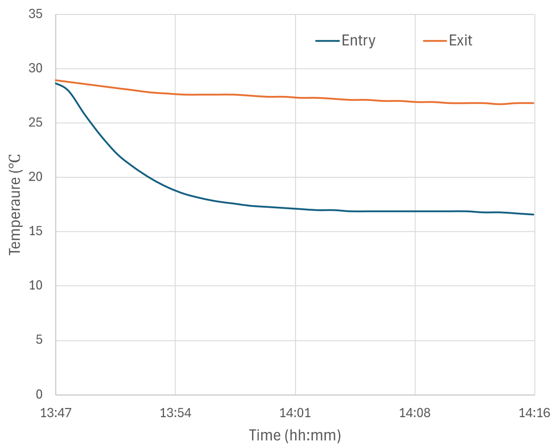

Figure 5. Temperature Data of Air Entering and Leaving the Internet Hub was Measured Using the USB Temperature Probes from 1:47 p.m. to 2:16 p.m. on Tuesday, 7 October 2023. During the first 14 minutes. The Two Temperature Probes were Equilibrating

The Future of Data Centres

A critical issue to discuss is the negative environmental impact caused by the continuous operation of data centres. Data centres use a substantial amount of energy on a daily basis and directly and indirectly emit potent greenhouse gases such as carbon dioxide. In addition, they use backup diesel generators and battery storage to mitigate power outages and use prodigious volumes of fresh water for cooling (Glanz, 2012). Consequently, solutions must be developed to reduce data centres' carbon and energy footprint.

It was estimated that data centre energy consumption during 2022 was 30 GW, or ~1% of total world energy use (Glanz, 2012). The amount of data processed by data centres doubles approximately every four years (LightEdge 2023), which is completely unsustainable. On the current trajectory, cloud energy requirements will exceed the 2024 total global energy consumption by 2052. It is pertinent to note that the problem of increasing data centre energy consumption was flagged before the current surge in the use of AI (Jones 2018).

DNA versus silicon

Suppose the current rate of increase in data storage is to be maintained without an exponential increase in energy requirements. In that case, some means of storing data using less energy is urgently required. A promising candidate is DNA storage, which has a much higher data density than silicon devices and a much lower energy cost (Dong et al., 2020). DNA has significant structural integrity and stability. For example, seeds, thousands of years old, have been germinated, meaning DNA can still be viable long after it has been created.

A date palm seed, over 2,000 years old, as revealed by radiocarbon dating, was germinated in 2005 (Sallon, 2008). The seed was excavated from the ruins of Masada in 1963-1965 and stored at room temperature for the next 40 years until germination. This is definitive proof of the long-term survival of DNA without the expenditure of any energy.

However, DNA is susceptible to damage and mutation from cosmic rays and high-energy ionising radiation such as X-rays and gamma rays (Willers et.al., 2004; Globus and Blandford, 2020). This may restrict the use of DNA storage systems to certain locations at lower altitudes and distant from potential emitters of high-energy ionising radiation.

DNA's breakdown temperature is 190°C. In contrast, computer chips become damaged at temperatures above approximately 80°C. Twist Bioscience (https://www.twistbioscience.com/) has demonstrated the potential of DNA storage by storing the first series of the Netflix series *Biohackers* on DNA. Recently, 16 GB from the Wikipedia online knowledge repository was encoded onto strands of DNA (Shankland, 2019).

Students in secondary school mathematics and physics classes can perform calculations similar to the following example. The nucleus of a human cell contains 23 pairs of chromosomes (46 in total), with each chromosome containing 3 billion base pairs. Each pair of chromosomes contains duplicate information. DNA's ability to divide is useful for generating backup data.

Since there are four amino acids used to encode the genetic information, each amino acid can code for two bits as follows: adenine: 00, guanine: 01, cytosine 10, thymine: 11. Therefore, in terms of unique information (non-duplicate) each 3 billion base strand of DNA can store $3 \times 10^9 \times 2 = 6 \times 10^9$bits, which is equal to $(2 \times 10^9)/8 = 2.5 \times 10^8$ bytes which is equal to 250 MB.

All 46 strands of DNA can be store $23 \times 250 = 5750\ \text{MB} = 5.75\ \text{GB}$ d, which is comparable to the storage capacity of a single-layer DVD (4.7 GB). The nucleus of the human cell is a sphere $\sim 10\ \mu m$in diameter. If we imagine this fitting into a cube $10\ \mu m\ (10^{-5}\ \text{m})$with sides, this is a volume of $10^{-15}\ \text{m}^3$.

The UQ Data Centre currently has 17 PB (10^{15} bytes) on disc and 40 PB on tape, totalling 57 PB, or 57 000 TB. Therefore, using the rule of thumb that 5.75 GB can be stored in a volume $10^{-15}\ \text{m}^3$ using DNA storage, the same density as in the human nucleus, the volume required to store all the data in the UQ data centre is $((5.7 \times 10^{16})/(5.75 \times 10^9)) \times 10^{-15} = 9.9 \times 10^{-9}\ \text{m}^{-3}$

just ~10 cubic mm, comparable to the volume of a grain of rice. Consequently, data centres that use DNA data storage could require far less space, maintenance, and energy than current data storage systems.

Quantum computing

Quantum computing has been cited as a potential solution to the looming data centre energy crunch. There is much discussion about quantum supremacy, which is the point at which quantum computers exceed the capabilities of classical computers. However, the most significant immediate benefit of quantum computers may be greater energy efficiency by 100, although doubts have been expressed (Chen, 2023). Quantum computing could be included in a discussion of the physics of data centres. Students often know this topic from the media (Meyer, 2023).

Quantum computing is an advanced topic in physics and is not generally dealt with in high school or first-year undergraduate physics. However, some educators have developed ways of making the subject more accessible to a broader audience (Fitzerald 2024) and have reviewed how quantum mechanics is currently taught (Hughes, 2022, Krijtenburg-Lewerissa, 2017), and pointed out the need to get students ready for this emerging technology (Sing, 2022). The ultimate answer to the data centre energy crises may be biological quantum computers based on DNA (Riera Aroche, 2024).

CONCLUSION AND SUGGESTION

Quantifying and reducing the energy and greenhouse gas footprint of data centres is critical to keeping the average global temperature increase to less than 1.5 °Cdegrees Celsius by 2050. Consequently, this highly relevant topic can be incorporated into secondary school and university physics curricula to elucidate important concepts from both classical and modern physics.

Novel technologies such as DNA data storage can be employed to alleviate data centres' impact on the environment and the global energy budget. Simple computations that students can perform quickly, such as the 'DNA versus silicon' calculation shown in this article, clearly depict the potential of DNA data storage.

As an extension activity, students can obtain long-term temperature and/or energy usage recordings from various data centres and use these to calculate their yearly energy requirements. This can be used to directly evaluate the energy savings gained by replacing current data storage systems with DNA data storage. The topic of data centres comes under the remit of STEM. It connects physics, chemistry, biology, engineering, and mathematics.

AUTHOR CONTRIBUTIONS

SH and PS both conducted measurements in the UQ Data Centre. SH shared in writing and revising the paper.

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REFERENCES

Apata, G., Adebayo, A., & Ainah, P. K. (2022). Transmission Losses in Power Systems: An Overview, *Proceeding of the 1st ICEECE & AMF (2021), 1-6.* https://www.researchgate.net/publication/361094202_Transmission_Losses_in_Power_Systems_An_Overview

Chen, S. (2023). Are quantum computers really energy efficient?', *Nat Comput Sci* 3, 457–460. https://doi.org/10.1038/s43588-023-00459-6

Dong, Y., Sun, F., Ping, Z., Ouyang, Q., Qian, L. (2020). DNA storage: research landscape and future prospects', *National Science Review*, 7

(6), Pages 1092–1107, https://doi.org/10.1093/nsr/nwaa007

Fitzgerald, B.W., Emonts, P., Tura, J. (2024). A Christmas story about quantum teleportation', *Phys. Educ.*Vol. 59 (3) Pages 035021. DOI: 10.1088/1361-6552/ad2cf4 https://dx.doi.org/10.1088/1361-6552/ad2cf4

Globus, N. and Blandford, R.D. (2020). The Chiral Puzzle of Life', *The Astrophysical Journal Letters. Vol.* 895(1), DOI: 10.3847/2041-8213/ab8dc6.

Hughes, C., Isaacson, J., Turner, J., Perry, A., Sun, R. (2022). Teaching Quantum Computing to High School Students', *Phys. Teach.* 60 (3): 187–189. https://doi.org/10.1119/10.0009686

James, G. (2012), Power, pollution and the internet, The *New York Times.* https://www.nytimes.com/2012/09/23/technology/data-centers-waste-vast-amounts-of-energy-belying-industry-image.html

Jones, N. (2018). How to stop data centres from gobbling up the world's electricity', *Nature*, 561(7722):163-166. doi: 10.1038/d41586-018-06610-y. PMID: 30209383.

Krijtenburg-Lewerissa, K., Pol, H.J. Brinkman, A., van Joolingen, W.R. (2017). Insights into teaching quantum mechanics in secondary and lower undergraduate education', *Physical Review Physics Education Research 13* (1) Pages 010109 DOI:10.1103/PhysRevPhysEducRes.13.010109 https://link.aps.org/doi/10.1103/PhysRevPhysEducRes.13.010109

Lee, T. (2021). Scaling renewable energy technologies:Challenges and opportunities. *Urban Energy Journal*, *5*(3), 89-101

LightEdge. (2023). The Data Explosion and Hidden Data Storage Costs in the Cloud – Could Object Storage Be the Answer? https://www.lightedge.com/blog/the-data-explosion-and-hidden-data-storage-costs-in-the-cloud-could-object-storage-be-the-answer/#:~:text=Recent%20research%20forecasts%20a%2022,of%20stored%20data%20in%202020.

Meyer, J.C., Pollock, S.J., Wilcox, B.R., Gina Passante, G. (2023). How Media Hype Affects Our Physics Teaching: A Case Study on Quantum Computing'. *Phys. Teach.* 61 (5): 339–342. https://doi.org/10.1119/5.0117671

Riera Aroche, R., R., Ortiz Garcia,Y.M., Martínez Arellano, M.A., Riera Leal, A. (2024). DNA as a perfect quantum computer based on the quantum physics principles', *Sci Rep* **14**, 11636. https://doi.org/10.1038/s41598-024-62539-5

Ryan, St. (2023). Exponential data growth could turn storage for AI into an information supply chain, *Silicon Angle*. https://siliconangle.com/2023/08/03/exponential-data-growth-could-turn-storage-for-ai-into-an-information-supply-chain-ibmstoragesummit/

Sallon, S., Solowey, E., Cohen, Y., Korchinsky, R., Egli, M., Woodhatch, I., Kislev, M. (2008). Germination, Genetics, and Growth of an Ancient Date Seed. Science, 320(5882), 1464–1464. doi: 10.1126/science.1153600

Singh, C., Levy, A., Levy, J. (2022). Preparing Precollege Students for the Second Quantum Revolution with Core Concepts in Quantum Information Science'. *Phys. Teach.* 60 (8): 639–641. https://doi.org/10.1119/5.0027661

Shankland, S. (2019). Startup packs all 16GB of Wikipedia onto DNA strands to demonstrate new storage tech -

Biological molecules will last a lot longer than the latest computer storage technology, Catalog believes’. CNET. Retrieved 15 February 2024.

Thoroughbrednews, 13 November 2023 https://www.thoroughbrednews.com.au/news/story/biggest-melbourne-cup-carnival-in-years-158543?section=industry#:~:text=It%20was%20also%2010%20Play's,audience%20increasing%2035%25%20on%202022.

Wehner, S., Elkhous, D., Hanson, R. (2018). Quantum internet: A vision for the road ahead’, *Science*, *362*(6412), 1-9. 10.1126/science.aam9288

Willers, H., Dahm-Daphi, J. and Powell, S. (2004). Repair of radiation damage to DNA, *British Journal of Cancer*. *90*(7), 1297–1301. https://doi.org/10.1038/sj.bjc.6601729

Yiming Dong, Fajia Sun, Zhi Ping, Qi Ouyang, Long Qian. (2020). DNA storage: research landscape and future prospects, *National Science Review*, *7*(6), 1092–1107, https://doi.org/10.1093/nsr/nwaa007.