A Review of Quantum Computer Energy Efficiency

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***Abstract*—Energy efficiency is crucial to protecting our planet from pollution and global warming disasters. Quantum computers offer a great opportunity for energy saving and fast computations. However, designing quantum computers faces numerous challenges. This paper presents a concise overview of quantum computer energy efficiency, and challenges.**

***Index Terms*—Quantum computing, quantum computer, energy efficient, power consumption, quantum annealer, superconducting.**

I. Introduction

Energy efficiency or (efficient energy use) is the main objective of every nation to save the planet of global warming, air quality, and overall pollution [1]. Reducing the amount of energy required to provide devices, services, and products is an essential goal to maintain our environment safe and suitable for human and all living beings [2].

The improvement of human's life such as creating smart cities, smart villages, and autonomous cars deduce to a massive amount of data and large computational problems that require powerful computational devices to process these amount of data and perform the requested tasks [3]–[5].

To solve complex problems and perform large computations, designing a powerful computer with large and efficient computational integrated circuits is a substantial stage. According to Moore's law [6], doubling the number of components per integrated circuit every year becomes impossible due to the classical physics restrictions which cause the overheating and damaging of the integrated circuit. Therefore, integrating multiple circuits to perform different complex tasks is one of the major solutions. Supercomputers are the main examples of such architectures. However, supercomputers require a massive amount of energy consumption to perform calculations which is very expensive and harms the environment.

Quantum computer designing idea was first proposed in 1982 by Richard Feynman [7], [8] as a computer that uses the quantum mechanical effects to perform computations. Quantum computers could be successful alternative devices to the supercomputers as they outperform the supercomputers in the computational speed. Moreover, quantum computers require smaller power consumptions compared to supercomputers. Therefore, quantum computers are more energy efficient than supercomputers. However, most of the existing literature and research studies target the quantum computer computational efficiency, neglecting the energy efficiency aspect. The development of quantum computer theory and computation were started since the late 1980s. However, designing a quantum computer machine physically was in the beginning of the 21st century due to devices limitations that required to design the quantum processor and measure its components.

In this paper, we target the energy efficiency aspect of the quantum computer. This paper shows a brief review of quantum computer energy efficiency preferences and challenges. Section II shows a brief introduction of the quantum computer evolution. Section IV shows a concise review of the energy efficiency of quantum computers comparing to the classical supercomputers.

II. Quantum Computers Evolution

The quantum computation theory was started in the early 1980s. The inception of the idea was to use quantum physics and mechanics concepts to perform computations [7]–[9]. While, the evolution of designing different quantum algorithm, computational components, and quantum gates was developed under the "Quantum Computing" research area [9], [10], developing of the quantum computer as a processing device did not actively investigated until the beginning of the 3rd millennium, when the first working 5-Qubits nuclear magnetic resonance quantum computer was demonstrated at the Technical University of Munich in Germany [11]. Then, at the Los Alamos National Laboratory in the United State, the first working 7-Qubits nuclear magnetic resonance quantum computer was demonstrated [11]. In 2002, the first working pure state nuclear magnetic resonance quantum computer was demonstrated at University of York and Oxford University. This computer design was based on parahydrogen [11].

The D-Wave Systems was demonstrated in 2007 by D-Wave Systems Inc [12], which is the world's first company to sell computers that use the quantum physics effects in their processes and operations. The first D-Wave System uses 28-Qbits quantum annealing computer [13]. Then, the evolution of quantum computer design purpose was to increment the number of Qbits to increase the computational performance of the quantum machine. In May 2011, D-Wave announced the developed 128-Qbits quantum annealing machine which was called D-Wave One. The D-Wave two was developed in 2013 as a 512-Qbits quantum annealing machine. Then, there were many different designed chips inspired by quantum computation based on superconducting systems manufacturing, and quantum computer chips. The most significant attempts were done by IBM-Q [14], Intel [15], and Google [16]. In

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2015, D-Wave 2X, which is an 1152-Qbits quantum computer was released. In 2017, D-Wave Systems announced a 2000Q computer which is a 2000-Qbits quantum annealer [17]. 2000Q is thousands of times faster than its predecessor quantum annealing computers [18]. In addition, it is faster than any supercomputer approximately by 3600 times and outperforms the regular computer chip speed by 100 million times [19]. The 2000Q quantum computer is shown in Figure 1. The D-Wave 2000Q system dimensions are approximately $10\text{ft} \times 7\text{ft} \times 10\text{ft}$ length, width, and hight respectively [17]. Therefore, it requires a large area space to be settled.

III. Quantum Computer Fundamental Principles

Quantum computers operations are based on fundamental principles of quantum mechanics. The two main principles are superposition and entanglement. This section gives a concise introduction to each of these main principles.

A. *Superposition*

The superposition principle of quantum mechanics is one of the major features of quantum computers design. From quantum mechanics theory, any two or more quantum states are assumed to be added together [20]. In other words, they could be superposed. The result of this superposing is another valid quantum state; and via versa [20]–[22]. Whilst, the quantum superposition representation holds multiple states at the same time.

In a classical computer, the register value could only on state at a time (either 0 or 1). But in the quantum computer, due to the superposition phenomena, the Qbit is represented as a linear combination of $|0\rangle$ and $|1\rangle$ at the same time. Where $|0\rangle$ represents the 0 state and $|1\rangle$ represents the 1 state in quantum computing [21], [22], [28].

B. *Entanglement*

Quantum computer could also present the quantum entanglement phenomena [28]. Entanglement phenomena happen when the quantum superposition state cannot be decomposed into its composition state [28]. In the entanglement state, it is impossible to determine the probability of observing one of the composition stated without considering the other states [21], [22].

IV. Quantum Computers Energy Efficiency

Quantum computers are significantly outperforming the classical personal computers and supercomputers in the computational speed and computational power [9], [10]. Moreover, quantum computers require much less power consumption compared to any supercomputer. This is because the quantum computers utilize the principle of quantum tunneling [20], [23], [24]. Table I shows a comparison between the existing commercially available annealing quantum processors designed by D-Wave and supercomputer average power consumption comparison [17], [25], [26] (excluding cooling requirements). Table I shows that the most powerful existing quantum computer to-date power consumption is smaller by 100 times than the supercomputer power consumption [17], [25], [26]. Therefore, the quantum computer is more energy efficient comparing to average supercomputer power consumption requirement.

Fig. 1: The 2000Q quantum computer size and final shape [17].

TABLE I: Power consumption comparison between the annealing quantum processors and the average power consumption for supercomputer [17]. the term “unknown” means there is no literature found that contains related information.

Design	***Power Consumption***
D-Wave One	unknown
D-Wave Two	15.5 kW
D-Wave 2X	25 kW
D-Wave 2000Q	25 kW
Supercomputer	2500 kW

Quantum computer could perform large tasks that require a large number of computations in a significantly smaller duration than the supercomputer. Therefore using the quantum computer instead of the classical computer could achieve the desired computational results using smaller energy requirements.

V. Quantum Computer Challenges

Quantum computers are significant tools to solve complex tasks and energy efficient. However, quantum computers are very expensive, D-wave 2000Q computer price is approximately \$15 million [27]. This because designing quantum computer hardware is extremely expensive due to the additional requirement to prepare the constraints under which the quantum processor could work. The quantum processor requires an additional cooling system to reach the -273°C (0.015 degrees Kelvin) which is cooler than interstellar space by 180 times [17]. In addition, the quantum processor requires a very low pressure to be able to work. For D-Wave 2000Q quantum computer, the pressure must be 10 billion times lower than atmospheric pressure [17]. Furthermore, the overall size of the quantum computer is huge. Therefore, the quantum computer nowadays could not be a portable device.

VI. Conclusion and Discussion

Quantum computer is a new era in energy efficiency studies. Quantum computer could be a great machine in processing data and problem solving. Quantum computers are significantly efficient comparing to the classical supercomputers from the power consumption and computational speed aspects. Quantum computer has been successful in specialized computations. However, it has not been a universal computation tool yet. Designing a quantum computer is still a considerable challenge due to several manufacturing issues. From the computational view, the quantum computer could replace the classical computers except for those algorithms that does not have a quantum computing counterpart yet [28]. However, from the hardware view, the existing quantum computer design is still an open area for developing the machine design and enhancing the additional requirements to have an available and less expensive computational device. These could increase the usage and of quantum computers to acquire their benefits in both computational and energy efficiency.

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