

Power Consumption Analysis of Computing Facilities with Superconducting Josephson Junction Quantum Computers

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Abstract—In this paper, the power consumption of present-day computing facilities which are based on Complementary Metal-Oxide Semiconductor Field Effect Transistor (CMOS) devices is compared with that of Josephson junction superconductor based computing facilities of the future. First, the amount of power used by present-day computing facilities was identified in different regions of the world. Then, the energy consumption of computing facilities of the future is presented considering superconducting Josephson junction devices as the primary building blocks of constituent quantum computers. From the results, it was identified that implementing superconducting devices in computing facilities could decrease the energy consumption by up to two orders of magnitude as compared to CMOS based semiconductor devices. The low power consumption and the fast operational speed of the Josephson junction superconductor based quantum computers were also identified to be superior than the semiconductor based computing facilities.

Keywords—power consumption; computing; superconductors; semiconductors; trade-off; improvement

I. INTRODUCTION

The functionality of traditional computers is based on storing data or information in electronic components such as transistors and memory elements. Data is stored in these components using a binary number format. The binary number format uses bits, which are a series of 1s and 0s. Bits can be manipulated between the 1 and the 0 states, or the 'on' and the 'off' states, with the help of computer algorithms.

On the other hand, a quantum computer uses the principles of quantum physics to increase the computational power of traditional computers. A quantum computer would store information as a 1 state, as a 0 state, or as a quantum superposition of the two states. Such a quantum bit representation, also referred to as a qubit format, allows far greater flexibility than the traditional binary system.

Since a quantum computer could perform calculations at a higher order of magnitude than traditional computers, it has attracted the attention of many researchers in the fields of cryptography and encryption. Some scientists are concerned that a successful and practical implementation of a quantum computer could potentially devastate the world's financial system by ripping through existing computer security

encryptions, which are based on factoring large numbers that, so far, cannot be solved by traditional computers within the life span of the universe [1]. A quantum computer could solve such problems in a practical amount of time.

Over the past half a century, a significant progress has been made in the field of superconducting devices from which the future day quantum computers could be constructed. The fundamental principle for these superconducting devices is based on two main achievements. The first one is the theory of superconductivity, also known as the BCS theory of superconductivity, derived by the American Physicists John Bardeen, Leon Cooper and John Schrieffer (BCS) in 1957 [2]. The theory described superconductivity as a microscopic effect caused by the condensation of electron pairs. These electron pairs are called Cooper-pairs as a tribute to Leon Cooper who showed that a small attraction between electrons in a superconductor can cause a paired state of electrons to have a lower energy than the Fermi energy, thus facilitating electron pairing and resulting in the phenomenon of superconductivity.

The second achievement is the discovery of quantum-tunneling by the British Nobel Laureate Brian Josephson. In 1962, Josephson predicted the tunneling of electron-pairs in a junction made of Superconductor-Insulator-Superconductor (SIS) materials [3]. This tunneling effect is a macroscopic quantum phenomenon that guides the principle of operation of superconducting electronic devices.

In general, superconducting electronic devices have numerous analog and digital electronic applications. The analog applications include Superconducting Quantum Interference Devices (SQUID) and millimeter-wave mixers whereas the digital applications include high-speed computer systems and quantum computers [4].

The Josephson microprocessor is one example of the quantum computer realization of superconducting devices [5]. Such microprocessors are based on Niobium and Aluminum Oxide (Nb/AlO_x/Nb) Josephson junctions which have uniform and stable characteristics. These microprocessors have a few thousand gates and a memory of a few kilobits. Therefore, when compared to the semiconductor microprocessors, they are not as large in size. However, they could be operated over ten times faster speeds [5].

Superconducting devices exhibit comparable characteristics with various semiconductor devices. While contemporary research in this area is focused on developing components of the future quantum computer from superconducting devices [6], [7], a study that analyzes and compares the device characteristics of superconducting devices with semiconductor devices is necessary to identify the applicability of these devices in computing facilities of the future. This paper addresses this research problem and aims to fill the gap in current literature regarding power consumption analysis of superconductor based computing facilities.

II. COMPUTING DEVICES OF TODAY

A. Number of Computers

According to the Internet Usage and World Population Statistics [8], as of June 30, 2012, there were approximately 2,405,518,376 computers in the world which are connected to the internet. This is 28.7% of the total world population. Of these, 273,785,413 or 11.4% were in North America. The United States alone accounted for 245,203,319 computers connected to the internet as of June, 2012.

In the United States, the annual computer and internet use by all the fifty states was censused and reported by the United States Census Bureau. For example, in the state of Tennessee, 78.8 % of households have had at least one computer at home in 2013. Using the state population of 6,454,914 for the year, this accounted for 5,086,472 people having access to at least one computer. Out of these, 63.1 % of household or 4,073,051 people in the state of Tennessee have had internet connectivity in the year. In Tennessee Technological University, there are 87 buildings, out of which 44 are occupied by offices and class rooms. In these 44 buildings, there are around 4840 operational computers.

B. Power Consumption of Computers of Today

According to the US Department of Energy, a typical desktop computer consumes between 65 W to 350 W, whereas a typical laptop computer consumes between 15 W to 50 W. For each of these computing facilities, the power consumption cost per year (pcc/year) can be calculated as given in (1).

$$\text{pcc/year} = (\text{rated power in kW}) * (\text{hours/day}) * (\text{days/year}) * (\text{cents/kWh}) / ((1000 \text{ W/kW}) * (100 \text{ cents/\$})) \quad (1)$$

With these power usages, at 11 cents/kWh, a typical desktop computer's energy usage costs vary from 20.88 \$/year to 112.42 \$/year. On the other hand, a typical laptop computer's power consumption costs vary from 4.82 \$/year to 16.06 \$/year. Uninterruptible Power Supplies (UPS) consume around 200 W to 1,000 W per average [4], which amounts to 64.24 \$/year to 321.20 \$/year. In addition, the total power consumption cost analysis (pcc_total) was performed as given in (2) and was calculated for the different regions based on the ratings of the computing facilities under the study as shown in Table 1.

$$\text{pcc_total/year} = (\# \text{ of computers}) * (\text{pcc/year}) \quad (2)$$

In today's internet computing era, data centers exhibit an increasing amount of power usage in the range of 100 MW to 500 MW. Internet companies like Google and Facebook are

building increasing numbers of data centers to support the growing number of internet users, who often have large amount of time spent online. For example, Google's data centers around the world consumed 260 MW in 2011 [9]. This amount of power is quite enough to power a city of 100,000 to 200,000 people [10], such as Knoxville, TN in the USA which had a population of 183,270 in 2013. Another internet giant Facebook has data centers whose power consumption could reach up to 78 MW [11], whereas Microsoft server farms around the world consume around 250 MW of electricity [12].

Conventional computing systems are mostly based on complementary metal-oxide-semiconductor (CMOS) switching devices and normal metal interconnects [13]. Recent technological trends and design tradeoffs between power consumption and clock frequency have brought CMOS to the limits of its scalability; therefore, alternatives to the CMOS technology must be found [14]. Using more efficient superconducting devices, the amount of power consumed by computing facilities could be reduced. Josephson junction devices are one of such devices whose low power consumption and high frequency characteristics could be explored to achieve a desired improvement. The next sections deal with these power consumption and time delay characteristics of Josephson junction based electronic devices for building the future computing facilities.

TABLE 1: CONSUMPTION COST FOR DIFFERENT POWER RATING COMPUTERS (\$/YEAR)

Region	Consumption Cost per Power Rating of Computing Devices			
	15 W	50 W	65 W	350 W
World (2,405,518,376 computers)	1.1595*10 ¹⁰	3.8633*10 ¹⁰	5.0227*10 ¹⁰	2.7043*10 ¹¹
North America (273,785,413 computers)	1.3197*10 ⁹	4.397*10 ⁹	5.7166*10 ⁹	3.078*10 ¹⁰
United States (245,203,319 computers)	1.1819*10 ⁹	3.9379*10 ⁹	5.1198*10 ⁹	2.7566*10 ¹⁰
Tennessee (5,086,472 computers)	2.4516*10 ⁷	8.1688*10 ⁷	1.0621*10 ⁸	5.7182*10 ⁸
Tennessee Technological University (4,840 computers)	2.333*10 ⁴	7.773*10 ⁴	1.0106*10 ⁵	5.4411*10 ⁵

III. COMPUTING DEVICES OF THE FUTURE

A. Transistor Count vs. Qubit Count

The qubit count of produced quantum processors has been increasing exponentially since the first practical implementation [15]. This growth is comparable to the observation for semiconductor devices made by the co-founder of Intel Corporation, Dr. G. Moore at the onset of the semiconductor integrated circuits (IC) era as shown in Figure 1 and Figure 2. Moore had predicted that the number of transistors on integrated circuits doubles approximately every two years [16].

B. Superconducting Josephson Junction Devices

The switching application of superconducting devices started in the 1950s with the application of a superconducting thin film wire called cryotron for switching a current path [17]. The challenge with the device was its slow switching speed. This challenge arose from the characteristic thermal transition of cryotron which was longer by more than 1 ns when compared to other semiconducting transistors. Later in 1966, IBM's Josephson project was prominent in developing computer components such as logic and memory circuits and advancing fabrication and packaging devices from superconducting Josephson junction devices [4]. Researchers in Japan also achieved to develop high-speed scientific computer systems using the Josephson junction superconducting devices and High Electron Mobility Transistor (HEMT) devices.

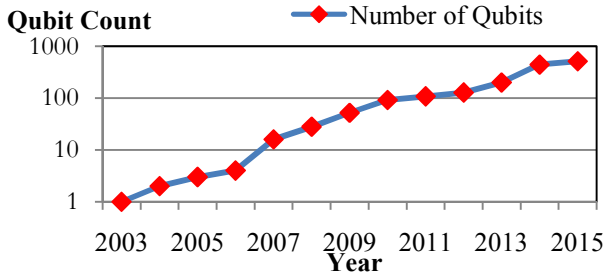


Figure 1: Qubit count of produced quantum processors per year [15]

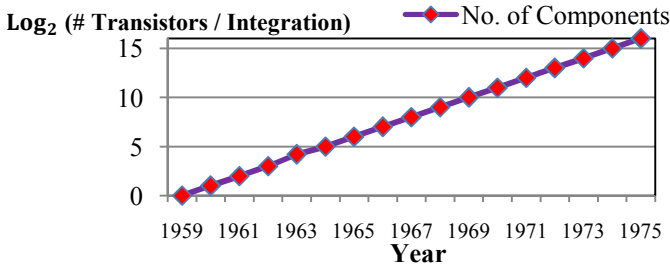


Figure 2: Number of transistors per integrated function per year [16]

C. Characteristics of Josephson Junction Switching and Logic Gates

The physics of using Josephson junction devices is based on a transition between logical states zero and one. Logical state zero corresponds to the superconducting state and the logical state one corresponds to the voltage state [4]. Moreover, Josephson junction devices have corresponding critical current of the junction represented as I_0 and a bias current I_g which is less than the critical current I_0 . When an input current I_c is added to I_g to make it exceed I_0 , the junction switches from the superconducting state to the voltage state. In this situation, most of the current from the junction is transmitted to the load resistance R_L since the load resistance is smaller than the sub-gap resistance of the junction as shown in Figure 3.

Two important time delays accompanying the switching of Josephson junction devices are the turn-on delay and the rise-time delay required for charging the junction capacitance [4].

Turn-on Delay: The junction is initially biased at $I_g = I_0$ in which case the junction phase is $\theta = \pi/2$. The bias current is then increased by ΔI . The turn-on delay required for the phase to reach $\pi/2 + 0.5$ is given in (3) [4]:

$$\tau_t \cong \sqrt{C_J \phi_0 / (I_0 \Delta I)} \quad (3)$$

where C_J and ϕ_0 are the junction capacitance and the flux quantum of the Josephson junction device. From the equation, the turn-on delay is proportional to junction capacitance $\sqrt{C_J}$ and inversely proportional to the bias current $\sqrt{(\Delta I)}$.

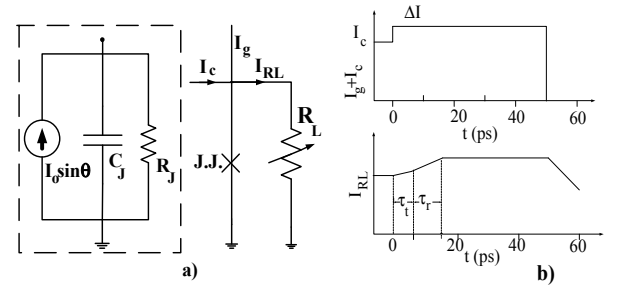
Rise-time Delay: is the time required to charge the junction capacitance, and is calculated in (4) [4]:

$$\tau_r = RC_J \quad (4)$$

where R is the effective resistance of the parallel combination of the junction resistance R_J and the load resistance R_L . Taking $R_L \ll R_J$, the rise time can be written as given in (5):

$$\tau_r = R_L C_J \quad (5)$$

The turn-on delay and the rise-time delay depend on the junction capacitance C_J as shown in Figure 3. To attain a smaller switching delay and a faster switching speed, the junction capacitance C_J and the junction size should be



reduced [4].

Figure 3: a) Equivalent circuit of the Josephson junction switch. b) Output current waveforms when the junction switches. Total switching delay = Turn-on delay (τ_t) + Rise time (τ_r) [4].

Some of the logic gates that could be constructed using Josephson junction devices include magnetically coupled gates and direct coupled gates [4].

D. Superconducting Interconnects

Computing devices of the future could be interconnected using superconducting wires between transistors and chips [18]. This could help improve computational speeds and reduce the amount of power consumption and power dissipation. Also, increasing component integration could reduce the speed of computation through superconducting interconnects.

E. Comparison of Josephson Junction Superconducting Devices to Traditional Electronic Devices

The main advantage of using superconducting Josephson junction devices over traditional electronic devices could be their low power dissipation and fast switching ability. The propagation delays of Josephson junction devices are less than 10 ps which is up to ten times lower than other semiconductor devices. Estimated power dissipations are 100 to 1000 factors less than most semiconductor devices. The characteristics of Josephson junction devices for practical propagation delay and power dissipation were specified in [4]. The frequency and power dissipation comparison is presented in Figure 4.

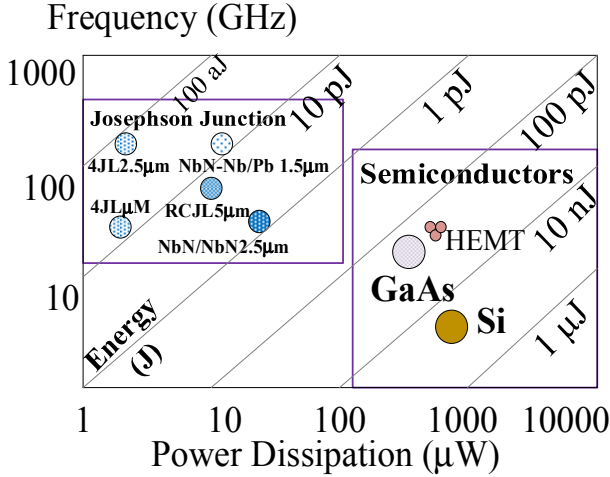


Figure 4: Comparison of frequency and power dissipation of Josephson junction switching devices to semiconductor devices.

Josephson devices exhibit lower propagation delay and low power dissipation. High Electron Mobility Transistor or HEMT are the next immediate hybrid semiconductor devices, which are comparable to Josephson junction superconductor devices for high-speed applications with very short switching time and low power dissipation [19]. The fact that Josephson junction devices have low power dissipation enables them to be densely packaged which thus decreases the length of the circuit interconnects. It could also increase the aggregate speed of computation in these devices.

IV. POWER CONSUMPTION ANALYSIS

Josephson junction superconducting circuits such as single flux quantum (SFQ) logic circuits have attracted the attention of researchers because of their expected low power consumption [20]. For computing applications, the static, dynamic and leakage power consumption of these devices is compared in this paper with those of semiconductor devices.

Furthermore, in semiconductor devices, data is transmitted and stored in forms of dc voltages, however in Josephson junction superconducting circuits, data is stored using a single quanta of magnetic flux Φ_0 . This data is transmitted using very short voltage pulses $V(t)$ which are calculated as given in (6) [17] where $h = 6.626 \times 10^{-34}$ J.sec is Plank's constant and $q = 1.6 \times 10^{-19}$ Coulomb is the charge of an electron.

$$\int V(t) dt = \Phi_0 = h/2q \approx 2.07 \times 10^{-15} \text{ Wb} \quad (6)$$

The magnetic flux Φ_0 could be computed from the critical current of the junction I_c , the resistance R_n and the frequency of switching f_i as given in (7).

$$\Phi_0 = I_c R_n / f_i \quad (7)$$

The dynamic power consumption for switching of a Josephson junction gate P_{JJ-D} at switching frequency f_i is then calculated in (8).

$$P_{JJ-D} = I_c^2 R_n = I_c \Phi_0 f_i \quad (8)$$

For Josephson junction devices with N_{sw} number of switching bits, P_{JJ-D} can be calculated as given in (9).

$$P_{JJ-D} = I_c \Phi_0 f_i N_{sw} \quad (9)$$

The static power consumption P_{JJ-S} for n Josephson junctions with a bias current I_b and a bias voltage V_b is independent of frequency and is calculated as given in (10) [21].

$$P_{JJ-S} = n I_b V_b \quad (10)$$

The total power consumption P_{JJ-TOT} is computed from the static and dynamic power consumption as given in (11).

$$P_{JJ-TOT} = P_{JJ-S} + P_{JJ-D} = n I_b V_b + I_c \Phi_0 f_i N_{sw} \quad (11)$$

The bias current $I_b(t)$ can be calculated from the minimum current value I_m after a sequence of switching events with the maximum clock frequency as given in (12) [21].

$$I_b(t) = V_b / R_b + \exp(-R_b t / L_b) [I_m - V_b / R_b] \quad (12)$$

For a CMOS device, the dynamic power consumption P_{CMOS-D} is the sum of transient power consumption P_{CMOS-T} and the capacitive load power P_{CMOS-C} , as calculated in (13) [22].

$$P_{CMOS-D} = P_{CMOS-T} + P_{CMOS-C} = (C_{pd} + C_{ld}) V_{cc}^2 f_i N_{sw} \quad (13)$$

where P_{CMOS-T} is the transient power consumption, C_{pd} is the dynamic power dissipation capacitance, C_{ld} is the load capacitance, V_{cc} is the supply voltage, f_i is the input signal frequency, and N_{sw} is the number of switching bits. Moreover, the static power consumption is calculated from the supply voltage V_{cc} and the current into the device I_{cc} as given in (14).

$$P_{CMOS-S} = V_{cc} I_{cc} = n V_{cc} i_s (e^{(qV/kT)} - 1) \quad (14)$$

where i_s is the reverse saturation current, V is the diode voltage, $k = 1.38 \times 10^{-23}$ J/k is the Boltzmann's constant and T is the temperature in Kelvin.

The total power consumption $P_{CMOS-TOT}$ is the sum of the static and dynamic power consumption as given in (15).

$$P_{CMOS-TOT} = P_{CMOS-S} + P_{CMOS-D} = n V_{cc} i_s (e^{(qV/kT)} - 1) + (C_{pd} + C_{ld}) V_{cc}^2 f_i N_{sw} \quad (15)$$

V. RESULTS

For typical Josephson junction values of $n = 64$, $I_b = 350$ μ A, $V_b = 2.5$ mV, $I_c = 0.25$ mA and $N_{sw} = 4$ [17], [21], the power consumption of a Josephson junction device at 100 GHz is calculated from (11) as 56μ W + 0.207μ W = 56.207μ W.

This power consumption value was compared with that of a complementary metal oxide semiconductor (CMOS) gate. At practical values of $n = 64$, $V_{cc} = 2.1$ V, $I_{cc} = 20.723$ μ A, $C_{pd} = 1.05$ fF, $C_{ld} = 5$ fF, $f_i = 1$ GHz, $N_{sw} = 4$ [22], the calculation in (15) resulted in 2.785 mW + 106.722 μ W = 2.892 mW total power consumption of a CMOS device. As a result, the power consumption of a single flux quantum gate based on Josephson junction is 51.45 times smaller in magnitude than the power consumption of a CMOS gate. For other CMOS gates of critical current up to $I_{cc} = 40$ μ A, their power consumption reduction could reach a factor of 97.91, signifying a change of up to two orders of magnitude in power consumption.

The power consumption of a Josephson junction device and a CMOS were also compared as functions of frequency, critical voltage and current. It was identified that power consumption of binary operations using powers of two of switching bits in CMOS devices has a quadratic relation with critical voltage and showed larger power dissipation at higher values of frequency as compared to the Josephson junction counterparts as shown in Figure 5 and Figure 6. This indicates a significant promise of Josephson junction devices in the transition to low power consuming devices, especially at higher operating frequencies and higher number of switching bits. Expected improvement in power consumption of quantum computers of the future with the use of Josephson junction devices is presented in Table 2.

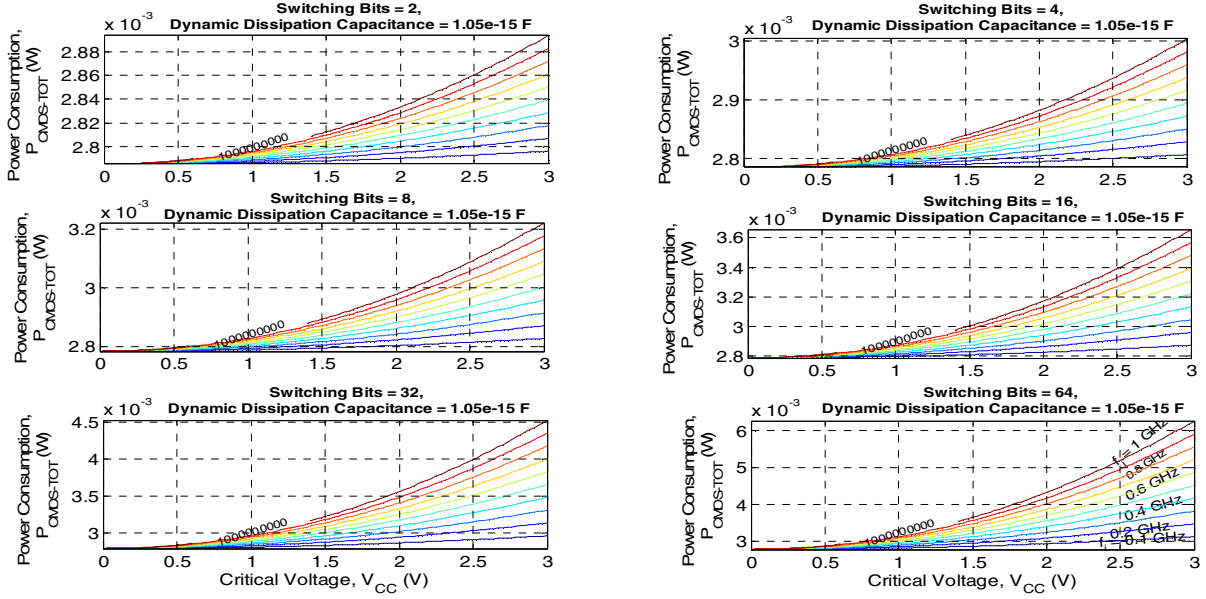


Figure 5: Power Consumption of CMOS devices as a function of critical voltage, critical current and frequency

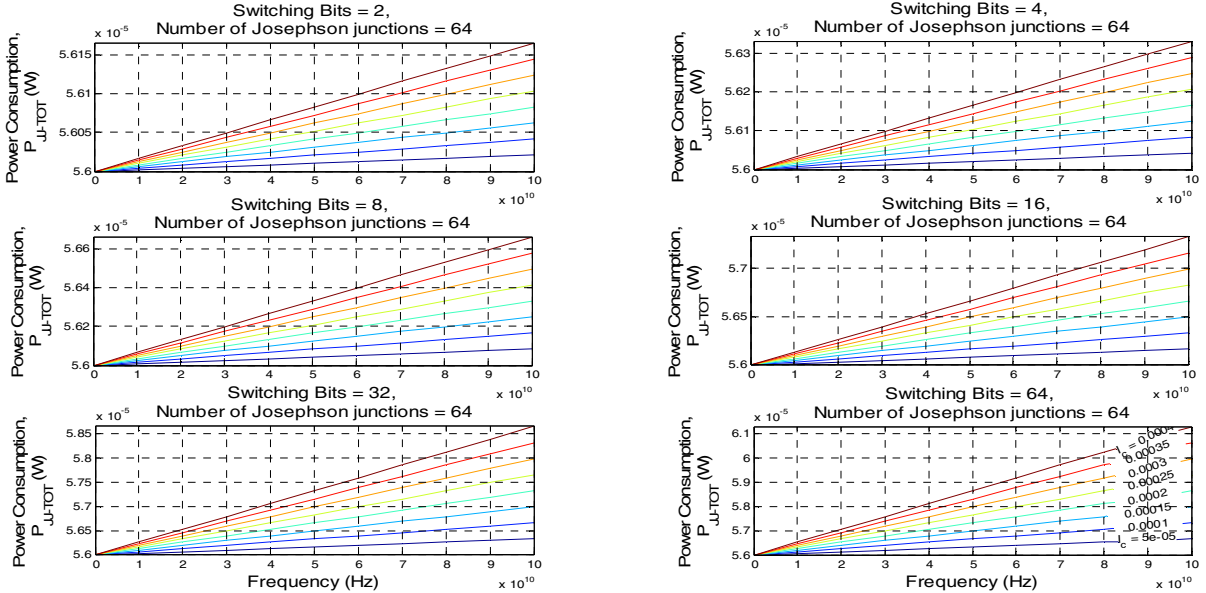


Figure 6: Power Consumption of Josephson junction devices as a function of frequency, critical voltage and current

TABLE 2: EXPECTED CONSUMPTION COST FOR DIFFERENT POWER RATING SUPERCONDUCTOR BASED QUANTUM COMPUTERS OF THE FUTURE (\$/YEAR)

Region	Power Consumption Cost per Rating of Computing Device			
	15 W	50 W	65 W	350 W
World (2,405,518,376 computers)	2.2536×10^8	7.5088×10^8	9.7623×10^8	5.2562×10^9
North America (273,785,413 computers)	2.5650×10^7	8.5462×10^7	1.111×10^8	5.9825×10^8
United States (245,203,319 computers)	2.2972×10^7	7.6538×10^7	9.951×10^7	5.3578×10^8
Tennessee (5,086,472 computers)	4.765×10^5	1.5877×10^6	2.0643×10^6	1.111×10^7
Tennessee Technological University (4,840 computers)	4.53×10^2	1.51×10^3	1.964×10^3	1.0575×10^4

From the results, implementing superconducting electronic devices in computing facilities could decrease energy consumption by a factor of 51.45 as compared to the CMOS based semiconductor devices. Other promising application areas of superconducting devices could be in the power transmission domain, where the zero electrical resistance of superconductors could result in reduction of energy dissipation up to 15 % of the generated energy. Furthermore, superconducting power electronic converters are promising technologies for their expected highly efficient power densities in critical application areas.

VI. CONCLUSION

A comparison of the power consumption of semiconductor based computing facilities and Josephson junction superconductor based quantum computers was presented for computing facilities of the future. Superconducting devices showed advantages of low power consumption and dissipation in computing facilities and power control rooms. Moreover, the low power consumption and fast speed of operation of the Josephson junction superconductor based quantum computers were identified to be far superior than the semiconductor based computing facilities. Since superconducting materials face challenges related to cryogenics and interference, the additional cost for keeping the appropriate environment could be considered in the future work. Thus, the superconducting technology could provide a great value in energy conservation of computing facilities and it could also help facilitate a smart transition towards an energy sustainable global environment.

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