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Review Article

Quantum batteries: Unlocking the future of high-tech energy storage

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ABSTRACT

The evolution of quantum batteries (QBs) lies at the core of the studies connected to the high-tech energy storage technologies. The non-traditional quantum systems make use of the entanglement and the coherence alongside the out-of-equilibrium to achieve the improvements in the charging rate, scaling of the energy capacity and size. This review provides insight into how QB models have evolved since their simple theoretical frameworks such as Dicke and Tavis-Cummings models to highly sophisticated structures of spin-chain structure, open/closed quantum system and random models. It has been discussed on the specialized properties of QBs that make them capable of super extensive charging and dark state-based energy storage robustness as well as comprehensive mathematical descriptions of these theoretical models. In this research, advances in QB technology, via research of superconducting circuits coupled with NV centers and molecular photonic systems that had reached room temperature operation are covered. Individual Hamiltonians Analysis has been done to determine how extractable work and charging speed are sensitive to system size and control field parameters and the strength of the coupling. Experimental research leads to the development of QB technologies using superconducting qubits, photonic micro cavities, spin-based systems and produces recent operational success using realistic parameters beyond low temperatures up to room temperature.

1. Introduction

The expanding world economy in the twenty-first century greatly depends on energy to power the industrial, transport, and domestic sectors, which has brought great environmental concern due to the fact that the main sources of energy are still fossil fuels. Petroleum, coal, and natural gas are sources of carbon-rich fuels, which provide nearly 36, 27, and 23.4 % of the global energy demand, respectively. The burning up of these fossil fuels emits almost 21.3 billion tons of CO_2 each year and this is a significant greenhouse gas that causes global warming and climate change. Besides the greenhouse gas emissions, mining and refining of fossil fuels lead to soil and water pollution, disturbance of the ecosystem and massive destruction of habitats. Recently, it has been stressed that a shift to the use of energy systems that are not based on fossils is a key to reaching the net-zero emission goals and addressing the risks posed by climate change [1,2]. This increasing energy needs resulted from industrial growth combined with population expansion and the shift to renewable energy systems reveal various limitations of conventional storage technologies especially Lithium-ion batteries (LIBs) [3–8]. LIBs fulfil their wide industrial functions in portable electronics, electric vehicles and grid storage but encounter multiple serious obstacles that impede their sustainability. LIBs show high thermal sensitivity, low energy density and high diffusion barrier. The safety hazard increases in multiple applications when extreme operating conditions occur or physical damage affects the battery [9–12]. The performance and functionality of LIBs decline throughout their operational period. The available research shows LIBs maintain 80 % of their original capacity throughout 500 recharge cycles although they become inadequate for applications that need extended energy efficiency. The depletion of performance in LIBs operating on the basis of from electrolyte decomposition together with electrode deterioration and lithium plating [13–16]. Sustainability regarding lithium-ion battery production faces additional challenges because of environmental as well as ethical worries during their production process. The extraction process for

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essential materials including lithium and cobalt and nickel causes environmental destruction that results in both water contamination and unprofessional labor treatment methods. The recycling facilities for LIBs have limited development which results in substantial waste generation and diminished resources [17–19].

Multivalent-ion batteries as promising alternatives with four primary candidates including magnesium together with calcium, aluminum and zinc-ion batteries. The batteries incorporate multiple valence ions like Mg^{2+}, Ca^{2+}, Al^{3+} and Zn^{2+} as charge carriers that enable larger theoretical power storage while decreasing the need for lithium or cobalt materials. The search for stable electrolytes with high conductivity continues to be a major obstacle since traditional LIB electrolytes fail to work with multivalent cations because of their high reactivity and passivation problems [19,20,21–26].

The research on QBs presents itself as a transformational solution because of established limitations within lithium-ion technology alongside challenges in multivalent-ion battery implementation. Application of quantum mechanics principles in the powering of energy storage is an innovative technology that could possibly revolutionize the existing power of storage. QBs are more superior to the normal electrochemical batteries as they achieve a higher level of efficiency as well as faster charge rates combined with increased storage capacity of energy through the application of quantum superposition, entanglement and coherence. The quantum superposition capability of placing a battery in a non-monochromatic energy state allows the battery to transfer energy faster hence accelerates charging mechanisms [27]. The quantum entanglement technology that entangles the particles and makes them interconnected provides possibilities of collective energy storage and retrieval processes that increase performance and reduce the charging times [28]. QBs exhibit the appropriate attributes to exploit in the future as powerful devices that can find applications in the quantum computing system, portable electronics, and renewable energy storage.

The concept of First QBs proposed by Alicki and Fannes in 2013 [29,30], has become an interesting way to store energy [31,32]. QBs are quantum mechanical systems which are quantum systems and take advantage of the underlying quantum mechanics to charge, store and release energy. The energy storage mechanism in such QBs exists in energized quantum system states although charging or discharging requires coherent superposition establishment between various states [33]. The charging power of various quantum devices exhibits super extensive scaling properties due to entangled effects and non-classical correlations. Ferraro et al.'s [28] original design (shown in Fig. 1) of a laboratory, produced QB model used N two-level systems coupled with an optical cavity to create a solid-state device. This device called "Dicke QB" demonstrated excellent super linear charging behavior because its collective cavity-mediated behavior showed an improvement scaling as $\sqrt{N}$. It works as a theoretical construction following the principles of the Dicke model in quantum optics that shows how multiple two-level quantum systems (qubits) and a shared electromagnetic field such as cavity or photon mode interact together. Within a Dicke QB, the coupled qubits interact together as a hybrid system because they strongly connect to a single cavity mode. Super enhanced energy exchange happens in super radiance because multiple qubits interact with each other while emitting or absorbing energy at faster rates than normal. The cavity receives energy during charging and distributes it in total to all qubits by virtue of their common interactive relationship. The collective charging mechanism which is quantum coherence between qubits is based on the fact that their operation is united into one system. The energy storage mechanism generates high correlation among the components of the system that enables ease in extracting the energy during the discharge phase. The study results indicate that N-entangled quantum bits are N times more powerful to charge than the non-interacting N quantum bits. Two kinds of properties can be observed in this physical system: extensive properties are dependent on the size of the system and intensive variables are not dependent on the size of the system [28,30].

The invention of QB offers good opportunities to come up with the energy storage apparatus that charges at higher speed. Experimental implementation of Dicke QB is still in a heavy developmental stage, and so, theoretical research on QBs has so far been carried out. The research in quantum optics and cavity quantum electrodynamics (QED) as well as materials science must be improved to address the problems with decoherence, scalability and sensitivity to temperature. For instance, experimental results utilizing superconducting qubits along with photonic cavities show that Dicke QB implementation becomes possible because strong coupling mechanisms can be achieved in superconducting qubits [32,34]. The future of energy storage is expected to change dramatically because the Dicke QB possesses the potential to use quantum mechanics for reaching revolutionary efficiency and performance capabilities. Other theoretical models beyond Dicke exist to investigate QB behavior. The Tavis-Cummings model extends the Dicke model by introducing cavity quantum electrodynamics (QED) phenomena for QBs to interact with quantitative fields inside microwave or optical cavities [35]. Two distinct research approaches using circuit QED and trapped ion systems have been developed for examining QB implementations in laboratory [36,37]. QBs produce superior capabilities than ordinary batteries by using super absorption mechanisms in quantum cells allows quantum speed up to charge devices at ultra-fast rates, as the number of quantum cells increases energy transfer

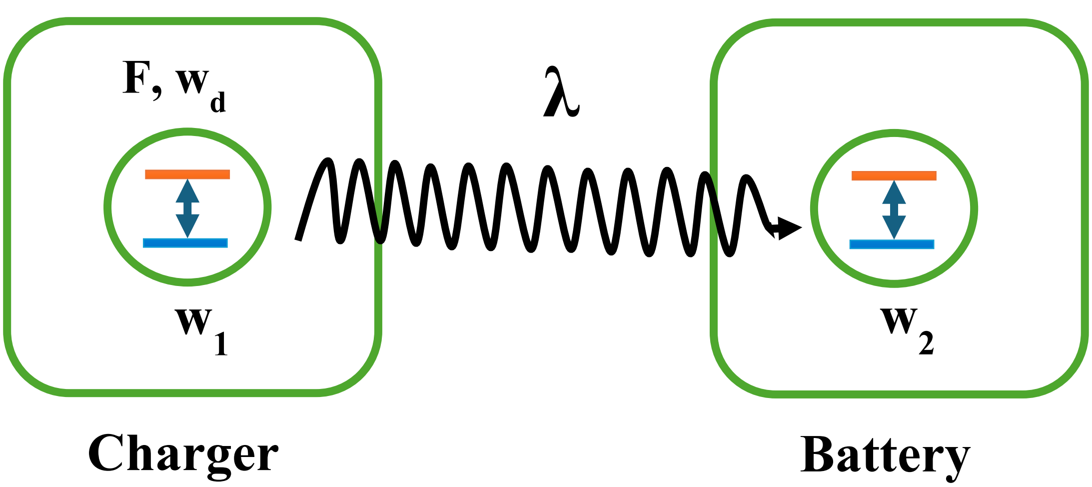

Fig. 1. The presented QB model appears in this schematic diagram. Between the charger and the battery exists two-level systems which operate at transition frequencies ω_1 and ω_2. Their individual reservoirs contain them while their connection happens through coupling strength λ. An external classical field operates the charger at the combination of strength F together with frequency ω_d.

efficiency [38]. Entanglement combined with coherence enables collective energy storage to achieve better capacity than conventional energy storage devices [39]. The attractive features of QBs make them suitable for various uses in quantum computing applications and nano devices and energy efficient quantum networking systems [40].

Several experimental implementation hurdles prevent the realization of QBs from their theoretical concept. The primary concerns in QB development include preserving quantum coherence properties and also obtaining adequate control of quantum interactions and developing workable realizations of solid-state systems. Recently, scientists have come up with new methods that combine light-matter interaction to superconducting qubits alongside engineered quantum reservoirs to maintain battery coherence and an increase in performance [41–43]. The QB development in this context will necessitate that experimental implementations are made that will facilitate the establishment of a gap between theoretical and practical implementations.

Various experimental models of QBs are available [32,44,45] although only partial demonstrations of fully operational QBs have been verified in different research studies [46–49] to date. These include the ultrafast pump-probe spectroscopy demonstrating super absorption in micro cavities with organic molecules [47], 2 min of energy retention with single-spin QBs [48] and charging and energy storage ability with single-qutrit QBs [49].

The experiment explores QBs beginning with their theoretical foundations and then proceeds to experimental progression and concludes with projections. The discussion of significant system models reveals the practical use and outlines challenges that developers must overcome to use quantum advantages in storage systems. By integrating the quantum theory with experimental developments we attempt to provide a comprehensive review as to the potential and feasible nature of quantum batteries.

2. Theoretical foundations of quantum

The fundamental theory of QB's is based on the regulated storage of energy in discrete quantum states. Upon interaction between a photon of an external light source with an atom or a two-level quantum system (i.e. a quantum dot or a superconducting qubit), the system can absorb the energy of the photon and, accordingly, switch between its ground-state and excited-state. The energy that is absorbed is stored in the population of these excited states which forms the charged state of the QB. The physical implementation of these quantum systems takes place in a common physical system, where the system is contained within a semiconductor microcavity that is surrounded by two very highly reflective mirrors, which contain and direct the light field. In case photons in a laser pulse are sent into the cavity, they drive the quantum system coherently to excited states charge the QB. This persistent excitation may then be emitted as work upon causing a controlled reversion to the ground state and allow extraction of energy on demand (as shown in Fig. 2). After excitation, electron quickly recombines to hole generated in lower state (discharging). To stop instantaneous recombination, dark state is generated. In dark state neither energy is emitted nor absorbed. Battery in dark state have high structural symmetry as a platform for storing exciton energy, in this state network can't exchange energy with its environment which indicates that system becomes immune to all environmental influence thereby attaining high degree of robustness to energy loss. General method of discharge stored energy from battery is involving breaking structural symmetry of network by taken out battery from dark state in control way.

Dark states are very important in improving the energy retention of QBs by averting radiative losses. They are the collective eigenstates which decouple with the environment, i.e. their excitations are not able to emit spontaneously energy to the environment. In experimental platforms, the creation of dark states has been accomplished in several platforms. Dark states in cavity and circuit QED apparatuses based on the Dicke model Dark states are produced by putting two-level systems (TLS) into antisymmetric superpositions, in which collective emission is destructively interfered [32,35]. The dark states of solid-state or atomic ensembles are typically prepared by use of coherent population trapping (CPT) or Stimulated Raman adiabatic passage (STIRAP) schemes [36] by which the population is transferred to a non-emitting ground-state superposition. They can be created by the fine-tuning of the emitter-chamber association and detuning of an eigenstate in which the photonic component of the eigenstate is almost zero in hybrid nanophotonic devices that include quantum dots in the microcavity. Experimentally, entering a dark state is characterized by a strong suppression of fluorescence or cavity photon number and the emergence of long-lived population trapping, and leaving the dark state by a burst of super radiant emission which is a signature of the release of stored energy. There is however, an important trade-off, namely, that dark states enhance stability of storage of energy, but also slow down charging and discharging rates since the very decoupling that suppresses losses in energy storage also introduces a constraint to the ability to couple to the charger or load. This requires more fields of control to lift the dark symmetry at discharge covering an intrinsic tradeoff between stability and operating speed in a QB based on dark states.

However, dark state is difficult to achieve, simplest way to attain dark state is by manipulating spin of electron, often called as spin forbidden transition accomplished by applying magnetic field. Battery contained collection of two half spin entangled particle. These particles interact in specific way that allows energy to be trapped and release when needed. It doesn't require external electric field for charging like traditional batteries instead internal time dependent modulation of quantum parameters within system changes the battery, essentially particle spin state manipulation to store and release energy [46,50].

The fundamental aspect of QBsexists in their Hamiltonian representation because it defines how the energy-storing system interacts with the charging mechanism. In general, the QB system is described by the total Hamiltonian (eq. 1) [51]:

$$H = H_{QB} + H_{Charger} + H_{int} \tag{1}$$

The Hamiltonian consists of three elements, H_{QB} designates the QB energy (two-level system) while $H_{Charger}$ represents the energetic system (external field or quantum cavity) and H_{int} defines the interaction mechanism between charging system and battery. The charging efficiency that material receives and discharging performance it outputs is

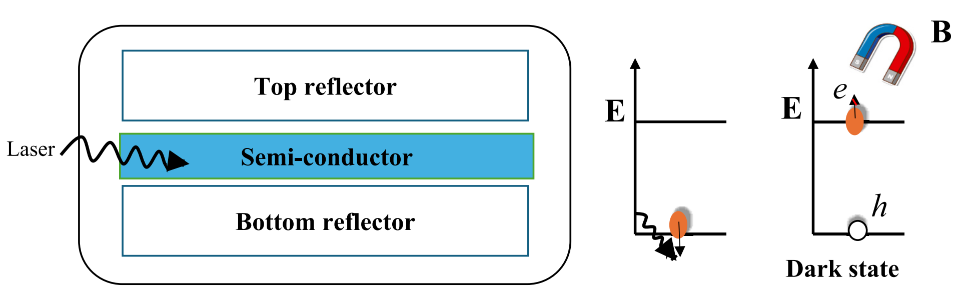

Fig. 2. General set up of QB.

directly influenced by the way these two elements engage with each other. This model presupposes the finite-dimensional closed system with the charger as an external field or cavity and the battery is a two-level quantum system (TLS). The first state is supposed to be either pure or thermal, and is not connected to the environment, except were stated in H_{int}. It makes perfect control assumptions of all the Hamiltonians and unitary dynamics, without decoherence or dissipation. Nevertheless, this idealization does not take necessary noise in the environment, temperature variations, and relaxation mechanisms, thus making it a less useful practice [51].

2.1. Dicke model: collective charging and super absorption

The initial theoretical model established for QBs is the Dicke model that represents multiple TLSs interspersed with one single-mode cavity field manner. This model presents its Hamiltonian operator as (eq. 2) [35,51]:

$$H = \hbar w_c a^\dagger a + \hbar w_a S_z + \hbar g(S_+ a + S_- a^\dagger) \tag{2}$$

This model features w_c as the cavity mode frequency together with w_a as the atomic transition frequency and S_z, S_+ and S_- as collective spin operators for the TLS ensemble alongside $a^\dagger$ and a as creation operators and annihilation operators of cavity photons, respectively, and g representing the TLS–cavity coupling strength. The super absorption phenomenon emerges through this model to produce charging rates that follow a relation exceeding standard charging rates. Dicke model Hamiltonian considers a set of identical TLS which interact with a common single-mode cavity field. It involves a constant coupling strength, complete coherence and is frequently based on the rotating wave approximation (RWA). Boundary conditions imply initially a vacuum cavity field and TLS in their ground state. This model is used to predict superabsorption and superlinear scaling of charging power. It is however constrained by the fact that it is highly sensitive to decoherence, cavity losses, and TLS inhomogeneity, and thus it is difficult to experimentally realize.

The model demonstrates super absorption through its $\sqrt{N}$ dependency which indicates that TLS density directly influences charging speed. The collective phenomena result in nonlinear increases of energy transfer efficiency contrasts against standard linear charging devices (lithium-ion batteries) [35,36,51]. Multiple limitations arise from the Dicke model since it requires perfect coherence which arises challenges as de coherence alongside dissipation effects quickly deteriorate system performance.

2.2. Tavis-Cummings model: quantum cavity charging

The Tavis-Cummings model [52,53] extends from Dicke model [35] to deliver cavity QED coherent interaction simulation as shown in Fig. 2. The Hamiltonian is shown in eq. 3 [52,53]:

$$H = \hbar w_c a^\dagger a + \sum_{i=1}^{N} \hbar w_a \sigma_z^{(i)} + \sum_{i=1}^{N} \hbar g\left(a\sigma_+^{(i)} + a^\dagger \sigma_-^{(i)}\right) \tag{3}$$

where σ_z, σ_+ *and* σ_- are Pauli matrices. The Tavis-Cummings model provides enhanced experimental implementation compared to the Dicke model as it introduces separate coupling strengths instead of using the symmetric collective interactions from the Dicke model [35], depicted in Fig. 3. Tavis Cummings model is a generalization of the Dicke model to include different couplings of each of the TLS to the cavity mode, but with RWA (Rotating Wave Approximation) and no TLS-TLS coupling. The model takes into account a closed system of qubits and a lossless single-mode cavity. It allows controllable coupling to be applicable to circuit-QED. Nevertheless, it is incapable of capturing strong many-body correlations or inhomogeneous broadening effects and it neglects cavity leaks so that it is less accurate at large or noisy systems.

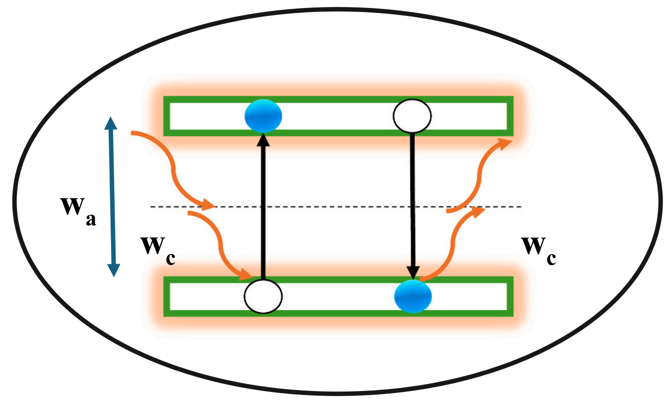

Fig. 3. Schematic representation of a QB, TLS with ωa level spacing, interaction between ground and excited state with frequency ωc of single cavity mode of through two-photon coupling.

The model fits perfectly into the operation of circuit-QED-based QBs because superconducting qubits serve as energy storage units. Controlled and adjustable coupling between battery and charger becomes possible through these setups to develop optimal charging techniques. However, this theoretical model fails to capture complete quantum many-body interactions because they play an important role in larger systems [39,52,53].

2.3. Spin-chain quantum batteries: distributed energy storage

A spin-chain model exists as a theoretical battery approach which describes the battery system as a chain of interacting spins that form the basis of its operation. The mathematical system representing such battery dynamics appears as (eq. 4) [54,55]:

$$H = \sum_{i=1}^{N} \hbar w_i \sigma_z^{(i)} + \sum_{i=1}^{N} J_{ij}\left(\sigma_+^{(i)}\sigma_-^{(j)} + \sigma_-^{(i)}\sigma_+^{(j)}\right) \tag{4}$$

The coupling strength between spins appears as J_{ij} in the Hamiltonian. The spin-chain model of the battery is used to describe the battery as a spin chain in nearest-neighbor exchange contact. Boundary conditions are open or periodic chains with a finite number of spins, which are initially at low temperature at the start of the process. It assumes homogeneous couplings, externally obtained fields of charge that are controlled. It has weak points of which are its fragile entanglement, extreme sensitivity to disorder and to decoherence, and difficulty in scaling to large systems due to the many-body interactions. The models facilitate distributed energy storage functionality besides supporting fast charging via entanglement-assisted functions. Localized form of energy transfer along with controlled management that spin-chain QBs offer is applicable to the solid-state quantum energy storage applications.

The primary task of spin-chain QBs is to store energy as a result of interaction between quantum states of adjacent spins with direction-changing magnetic capabilities. The operation of a distributed energy storage system is based on the quantum interactions that provide storage and transfer functionality based on the usage of these spins. Through quantum quenches that involve quick system parameter alterations or controlled external field applications the charging mechanism operates. Quantum control methods allow efficient power injection through their ability to utilize entanglement for improving storage capacity. Useful work becomes available for an external system through the evolution or relaxation of spin states during the discharging process as shown in Fig. 4 [54–56].

Various models based on spin chains have been developed for QB implementations because they demonstrate distinctive approaches to storing and releasing energy. The Quantum Ising Chain is a chain of interacting spins operated under transverse field system which enables

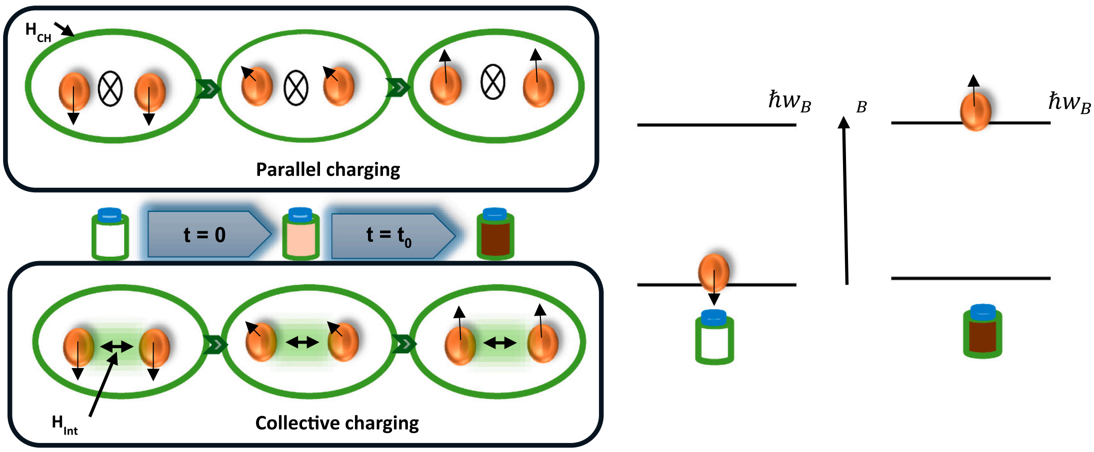

Fig. 4. Schematic diagram of two-cell QB the spin system obtains parallel and collective charging. The battery will be in the ground state (spin-down), but it will jump to the excited state (spin up) with maximum energy of QB in the time interval t. Cells are acted by external fields, and subsequently, assemble with each other through collective charging processes. The system progresses in various steps once charged in an entangled form.

the controlled storage and harvesting of energy [57–59]. Other effects in Heisenberg Spin Chains like Dzyaloshinskii-Moriya can enhance the ability of transfer of energy even though they have the innate capability to interact between spins [54]. The Cavity-Heisenberg Spin Chain is a further development in QB functionality due to its longer interaction ability that increases the stability of coherence and reduces power wastage [60,61]. Dimerized X-Y Chain is a model of an integral able that demonstrates a complicated quantum phase structure that allows the study of quantum phase transitions as they can influence the efficiency of energy storage and retrieval [62].

3. Fundamental operating principles

3.1. Quantum coherence and entanglement

The quantum coherence allows quantum systems to be many states at the same time. The coherent behavior is essential in the development of any of the QB functionality such as storage, transfer and retrieval of energy. The interacting dynamics of charged particle transfer are synchronized in different coherent quantum systems which leads to enhanced collective charging processes.

Entanglement connects multiple particles and leads to their strong correlation that allows them to be tied even when they are separated over large distances. QBs can utilize entangled quantum states to allow remote storage of energy and hybrid means of powering which increases the rate of charge and the efficiency of energy release. The energy distribution system, which has been made possible by quantum entanglement, has been able to stretch across a whole network hence optimizing the performance of charging in terms of fastening the speed of power delivery.

With the help of entanglement quantum batteries, it is possible to make the charging power equal to [63–65]:

$$\mathrm{P} = \frac{\mathrm{E}}{\mathrm{T}} \sim \mathrm{N}^{\alpha} \tag{5}$$

where, E is stored energy, T is charging time and N meaning the number of quantum units. a is a constant that is model specific and entangled systems scale with a similar behavior compared to a classical linear scaling. However, the external environmental interactions that produce de-coherence damage quantum coherence and entanglement which reduces the stored energy and efficiency of the battery system. A subsystem is made up of N subsystems that act in an ideal manner. The boundary conditions involve closed systems in the absence of noise in the environment. Although it shows that power can scale super-linearly, this cannot hold when there is decoherence or local noise, so super-linear power scaling is hardly ever feasible in experiments. The development of practical QBs requires successful de-coherence mitigation because this issue presents a significant technological barrier that scientists address through quantum error correction methods and reservoir engineering techniques [63–65].

3.2. Super absorption

The super absorption allows quantum subsystems to cooperate between them in order to achieve energy absorption rates which surpass standard classical models. This process occurs due to the constructive interference that exists between molecular excitation pathways. Charging time decreases because grouped molecules experience increased absorption strength that exceeds the total absorption of separate molecules. It accelerates the charging rates in QBs not only through quantum coherence but also through many-body interactions thereby enhancing performance of energy absorption.

The fundamental design of QBs is many quanta TLS that are coupled together by a shared electromagnetic field. Structured reservoirs like cavities and waveguides which connect multiple TLS experience nonlinear scaling of their energy absorption rate because the total units increase at least quadratically. The entangled or correlated state formation causes changes to energy level transition probabilities which results in this scaling effect as a fundamental aspect of collective quantum phenomena [60–67].

The mathematical description of super absorption in QB energy absorption uses an operator representation described by the Hamiltonian term (eq. 6) [68–70]:

$$H = \sum_{i=1}^{N} \hbar w_i \sigma_i^+ \sigma_i^- + \sum_{i \neq j}^{N} g_{ij} \left(\sigma_i^+ \sigma_j^- + \sigma_i^- \sigma_j^+ \right) \tag{6}$$

where $\sigma^{\pm}$ ladder operators for the ith quantum state, frequency w_i called transition defines the interaction between subsystems and g_{ij} is interaction strength. The super absorption Hamiltonian is used when there are a number of identical quantum emitters, interacting on a shared photonic mode or cavity, and they are collectively coherent. Boundary conditions entail a system that has an initially coherent system with negligible losses. This model however is very sensitive to disorder, detuning and leakage out of the cavity.

Super absorption is implemented in nano photonic and cavity QED systems which enable quantum emitters to optimize their energy transfer by using confined light modes. The ideal parameter control of the system parameters, i.e. spacing of emitter and cavity quality factor, allows the creation of a higher absorption region than the normal charging limit. Super absorption should be carefully controlled in QBs with somewhat enough interactions of light matter and coherence maintenance of a large number of body systems. Experimental barriers to the implementation of energy storage units and external fields are that researchers should be able to sustain strong coupling dynamics and limit decoherence-related losses. New research in quantum optics as well as cavity QED systems and engineered quantum reservoirs works toward overcoming these implementation difficulties thus advancing the practical use of QBs [68–70].

3.3. Dark states and local interactions

QBs use dark states as non-radiative states which fail to interact strongly with electromagnetic fields because of symmetry and destructive interference effects. QBs utilize dark states as critical energy stores that maintain the stored energy by blocking spontaneous re-emission which otherwise leads to power dissipation. Super absorption allows QBs to connect multiple charges while local interaction between qubits or molecules generates both improved energy absorption along with dark states creation. Such states become stable energy storage units because they do not interact with radiative channels. Local interactions through nearest neighbor coupling or short-range interactions produce dark states which keep stored energy trapped within the battery from the moment of charging until an external protocol induces its recovery. The combination of precise local interaction management with symmetry manipulation throughout QB design enables systems to store energy fast while maintaining its availability for long periods which resolves the essential challenge in developing usable quantum batteries.

A study has been conducted to achieve high energy storage and power by utilizing dark states along with local interaction [71]. This QB model operates differently from conventional QBs since it employs spin ensembles separated from each other while connected to a reservoir through localized interactions thus enabling both storage and transfer of energy. The research shows that the charging power capability reaches a direct proportion with the spin ensemble number N rather then $\sqrt{N}$ (according to Dicke model) [35,36,51]. The stable charged state functions without additional energy-consuming stabilization measures when the system remains connected to its surrounding environment.

The QB contains N_B spins operating as two-level systems which connect to an external thermal reservoir through its charger design comprising N_c spin excitable systems. It starts charging phase when the charger puts itself in direct touch with the battery through the reservoir connection. The controlling Hamiltonian for the system consists of terms describing battery store interactions as well as charger store interactions while integrating collective spin operators to describe the reservoir coupling effects (eq. 7) [71]. Quantum interferences create dark states which blocks complete battery discharge into the reservoir. The protection of stored energy occurs definitively in two-spin systems through complete decoupling of their antisymmetric spike state from environmental events. The storage capacity of the battery reaches higher levels during constant operational states as more spins are added to the system. A battery incorporating N_B spin components will store a greater amount of energy than N_B single-spin batteries of equivalent size.

$$H = w\left(J_B^Z + J_C^z\right) + \int dk E_k r_k^\dagger + \frac{g}{2}\left[\left(J_B^+ + J_C^+\right)R + \left(J_B^+ + J_C^+\right)R^\dagger\right] \tag{7}$$

where, the first term represents the energy of the battery and charger in terms of their collective spin operators $J_B^Z AND\ J_C^z$, where ω is the energy splitting of the two-level system (analogous to the energy levels of an atom). The second term represents the energy of the reservoir (which acts like a bath of electromagnetic field modes). The third term describes the interaction between the reservoir and the spins, where the raising (J^+) and lowering (J^-) spin operators allow for the exchange of energy between the spins and the reservoir. This model presupposes two distinct spin ensembles (battery and charger) that are locally coupled to a system of the common reservoir. Symmetric coupling is needed at the boundary conditions and initial states that are antisymmetric collective spin states that are decoupled with the reservoir, needed to support the formation of dark-states. It presupposes a small dephasing and localized interactions that are stable. Its major weakness is that dark states are delicate and hard to sustain in practice due to the fact that the slight asymmetry or noise can erase their decoupled property. The coupling strength g determines how strongly the battery and charger interact with the reservoir. This indicates that single battery with N_B spins stores more energy than N_B separate single-spin batteries [71].

4. QB models and architectures

4.1. Single qubit model

A single-qubit QB provides the basic model of quantum energy storage that stores energy within a two-level quantum system. The QB utilizes the Hamiltonian (eq. 8) [72]:

$$H_B = \frac{\hbar w}{2}\sigma_z \tag{8}$$

where σ_z is Pauli matrix and w denotes the energy spacing between $|0\rangle$ and $|1\rangle$ states [72]. The energy storage process takes place through under a time-dependent Hamiltonian (shown in eq. 9) with Rabi frequency Ω (determine charging rate) [28].

$$H_c(t) = \hbar\Omega\left(e^{iwt}\sigma_+ + e^{-iwt}\sigma_-\right) \tag{9}$$

The battery evolves under the unitary dynamics governed by $H_B + H_C(t)$ leading to energy transfer from the field to the qubit. The model (eqs. 8–10) supposes that the battery is represented by a single TLS qubit, which is motivated by a time-dependent field. Boundary conditions entail a qubit in an environment of perfect isolation which is in an initial ground state. It is based on the assumption of purely coherent and unitary evolution devoid of decoherence.

The stored energy in system is given by (eq. 10):

$$E = \langle \Psi | H_B | \Psi \rangle - E_{min} \tag{10}$$

where E_{min} is the ground-state energy. Maximum energy storage occurs when the qubit reaches the excited state $|1\rangle$ (fully excited) [72].

Single-qubit QBs have physical storage boundaries since maximum storage remains restricted to ħω which renders them unusable in practical applications. The Rabi oscillation frequency controls their charging speed making them constrained in efficiency for dynamic charging needs [34]. The absence of both entangled pairs and collective charging effects prevents the enhancement of single-qubit QB performance. The storage ability of these devices suffers from practical limitations because environmental de-coherence causes energy dissipation before extracting all stored energy. The extractable work remains limited due to unitary evolution because the stored energy cannot entirely convert into noticeable work.

4.2. Open quantum system model

Open quantum models of QBs explore how the charging and discharging occurs while batteries interact with an environment thus ensuring physical accuracy. Quantum systems in open configurations evolve non-unitarily under the Lindblad equation due to their engagement with external degrees of freedom instead of following single-directional unitary dynamical motions like closed systems. The battery operating under this model serves as a quantum system such as a qubit or a harmonic oscillator which interacts with a quantum charger and experiences environmental de-coherence and dissipation. The prominent battery modeling approach uses one or multiple two-level systems (TLS) linked to one or several bosonic or fermionic baths while showing specific processes of energy exchange with the charger and environment. The battery framework begins with a quantum system representation (such as a qubit or a harmonic oscillator) that connects to a charging system as well as experiences bath-caused de-coherence and dissipation effects. The model describes one or several TLS that interact with shared bosonic or fermionic baths, shows explicit energy exchange dynamics between charger and environment. Open systems maintain the enhancing power effects of coherence and entanglement in charging applications although these quantum benefits may weaken when de-coherence and noise affect the system.

Hadipour and Haseli present an open charge battery system that incorporates two qubits: a charging qubit and a battery qubit which face a High-Q cavity together with a classical driving field [73]. Through external field parameters the authors introduce a crucial innovation which controls energy exchange alongside de-coherence thus achieving enhanced charging capabilities with increased energy retention despite noise effects.

The system consists of two qubits A charger and B battery, each with transition frequencies ω_A and ω_B interacting with the vacuum modes of the cavity and a classical driving field of frequency ω_L as shown in Fig. 5. The total Hamiltonian of the system in the dipole and rotating-wave approximations is (eq. 11) [73]:

$$H = \sum_{j=A,B}\frac{w_j}{2}\sigma_Z^{(j)} + \sum_k w_K a_k^{+} a_k + \sum_{j=A,B}\left(\sum_k a_j g_k a_k \sigma_+^{(j)} + \Omega e^{iw_L t}\sigma_+^{(j)} + \text{H.c}\right) \quad (11)$$

where, a_k^{+}, a_k are creation and annihilation operator for kith cavity, $\sigma_Z^{(j)}$, $\sigma_+^{(j)}$ are Pauli and ladder operator for qubits and Ω is external classical field. System-environment interaction and coupling between cavity and qubit are $a_k$and g_k, respectively. The model (eqs. 11 & 12) is open QB which assumes that there are two qubits (battery and charger) coupled to a cavity and driven by a classical field and interacting with a Markovian environment. The conditions of boundaries are a weak to intermediate coupling of the system and environment and an initial thermal or vacuum state.

Applying rotational translation and defining detuning parameter $\Delta_j = w_j - w_L$, then effecting Hamiltonian as shown in eq. 12 [73]:

$$H = \sum_{j=A,B}\left[\frac{\Delta_j}{2}\sigma_Z^{(j)} + \Omega\sigma_x^{(j)}\right] + \sum_k w_K a_k^{+} a_k + \sum_{j=A,B}\left(\sum_k a_j g_k a_k \sigma_+^{(j)}\right) + e^{iw_L t} + \text{H.c} \quad (12)$$

Under weak coupling conditions the classical driving field Ω demonstrates essential importance when charging QBs because the qubits and environment link remains limited in intensity. An increase in driving strength Ω allows a substantial boost of stored energy and charging power to occur. The resonant countenance of the system leads to zero ergotropy value since when there is zero detuning [?]j between the qubit and the field the greatest extractable work of the system under unitary operations is zero notwithstanding the presence of energy storage. Detuning Δ_j of the system changes the system in that it generates non-zero ergotropy, that is, the battery is able to store non-zero

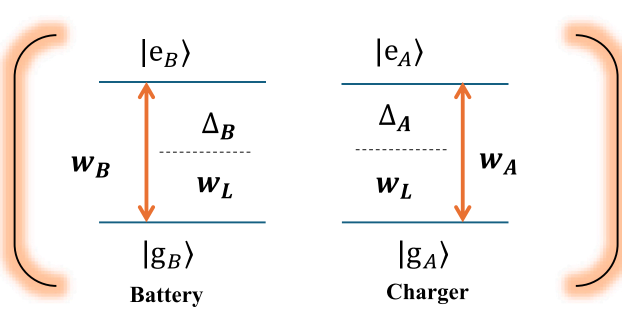

Fig. 5. A schematic representation of open quantum model.

ergotropy during non-resonant operations so forming a vital functional enhancement. At strong coupling regime, the interaction with the environment will dominate all other relations among the components of the system. The existence of a strong environment-induced coherence and the effects of memory in the presence of the strong environment enables the QB to retain energy and exhibit non-zero ergotropy behavior in the absence of the driving field of the classical. The introduction of classical field operations at strong coupling regime is further optimized by the enhancement of efficiency since environment correlations and coherent driving leads to a reinforcement of each other to enhance QB performance.

The detuning mechanisms have two variations of the associated effects. The higher the detuning of the qubit and the field, the better battery charging operation and ergotropy generation can take place and this parameter value can be regarded as one of the critical control parameters to achieve optimized battery operation. Detuning Δ_j between the classical field and cavity results in reduced charging power but sometimes creates conditions that enhance ergotropy which produces higher-quality stored energy despite a minor reduction in charging rate. The ability to precisely control open QB systems exists through alterations of coupling strength parameters g_k and detuning parameters Δ_j [74–76].

4.3. Closed quantum system model

The closed model of QB theory constructs isolated mathematical descriptions of battery systems and their charging unit which remain independent from environmental effects. Through this model the battery dynamics follow Hamiltonian rules and storage capabilities result from unitary transformations which affect the battery state. Closed models remain useful for initial theoretical studies but they do not represent actual QBs since these platforms always experience environmental interaction [77].

The general Hamiltonian for close quantum model is describe as eq. 13 [77]:

$$H(t) = H_0 + \lambda(t)H_1(t) \quad (13)$$

Here, H_0 *and* $H_1(t)$ are static battery Hamiltonian and time-dependent driving (charging) Hamiltonian, respectively. $\lambda(t)$ is control function (non-zero only during charging interval [0, T]).

The system evolves under Liouville-von Neumann eq. 14 [77,78]:

$$\dot{\rho}(t) = -\frac{i}{\hbar}[U(t), \rho(t)] \quad (14)$$

The stored energy at time t is (eq. 15) [77,78]:

$$E(t) = Tr[H_0\rho(t)] \quad (15)$$

The ergotropy $\varepsilon(t)$ (maximum extractable work) is (eq. 16) [77,78]:

$$\varepsilon(t) = Tr[H_0\rho(t)] - Tr[H_0\rho_{\text{Passive}}(t)] \quad (16)$$

Fu-Quan Dou et al. developed a QB model which operates as a closed loop three-level system through its battery system operating between three discrete quantum states $|\varepsilon_1\rangle$, $|\varepsilon_2\rangle$ and $|\varepsilon_3\rangle$ with energies $\varepsilon_1 < \varepsilon_2 < \varepsilon_3$, The charging process is realized by three laser fields that coherently couple all three transitions: $|1\rangle\leftrightarrow|2\rangle$, $|2\rangle\leftrightarrow|3\rangle$, and $|1\rangle\leftrightarrow|3\rangle$.

The interaction Hamiltonian under resonance becomes (eq. 17) [77,78]:

$$\text{H}_{\text{int}}(\text{t}) = \hbar\begin{pmatrix} 0 & \Omega_{12}(t) & \Omega_{13}(t)e^{i\phi} \\ \Omega_{12}(t) & 0 & \Omega_{23}(t) \\ \Omega_{13}(t)e^{-i\phi} & \Omega_{23}(t) & 0 \end{pmatrix} \quad (17)$$

These eqs. (13–17) are a model of an isolated system in which the battery dynamics as a unitary control system over time. The system begins in the ground state, and there is no environmental influence applied to it. It is based on perfect coherence, perfect control of driving fields and no dissipation. This is however not feasible in real devices as decoherence, fabrication imperfections and noise are not considered. It also puts an adiabatic condition that restricts the charge rate. The implementation of nonzero third control field $\Omega_{13}(t)$ within a three-level QB's closed-loop operation system produces greater ergotropy levels and average power output than when Ω_{13} equals zero. The system reaches higher efficiency for energy transfer because the closed-contour interaction creates phase-dependent coherence effects. Efficiency of energy transfer reaches its maximum state when using a driving-field phase ø equal to $\pi/2$. The battery performance optimization strongly depends on φ phase control since these parameters demonstrate periodic behavior with 2π periodicity. When the third control field uses modulation as $\Omega_{13}(t) = \Omega_0(1 - \cos(2\pi t/\tau))^2$ it produces the best possible system performance. The special functional pattern raises charging power at its average level to over eight times the amount achieved through an open-loop system. Under this configuration the battery charging process demonstrates four phases starting with a period of minimal energy accumulation followed by steady energy increase and finally oscillation from population transfers before reaching energy stabilization (Fig. 6) [78].

The protocol sets up starts the system from its ground state condition. STIRAP techniques [36] enable the system to traverse through an adiabatic path that should result in the fully excited state which represents a fully recharged battery.

Such a closed-loop QB model can achieve physical realization through diamond-based nitrogen-vacancy (NV) centers. The NV spin system includes a triplet spin-1 where levels exist $|-1\rangle$, $|0\rangle$and $|+1\rangle$ which can be mapped to $|\varepsilon_1\rangle$, $|\varepsilon_2\rangle$ and $|\varepsilon_3\rangle$,respectively. These levels can be driven coherently through microwave magnetic and strain fields. NV centers demonstrate promising potential for developing high-performance QBs because spin state initialization and readout operates at room temperature due to their spin-selective fluorescence properties [79].

4.4. Random QB model

Random QB (RQB) serves as a theoretical model created by Caravelli et al. [80] to study QBs through randomized initial conditions and evolution processes and stochastic Hamiltonians. The average work of

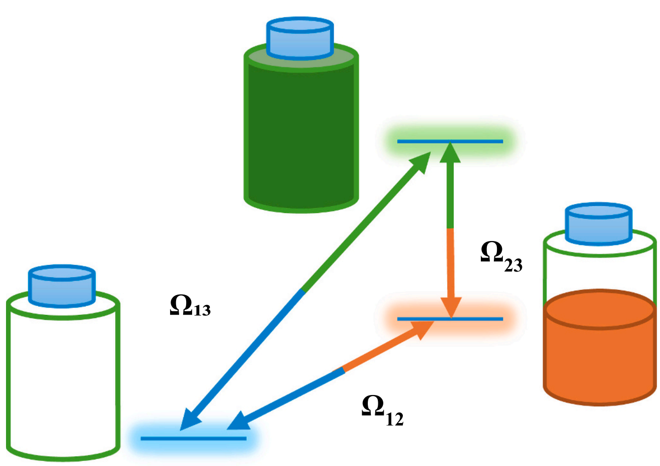

Fig. 6. Visualization of a closed-loop three-level QB. A battery exhibits three distinct states using energy levels while three specific laser beams charge the battery through Ω_{12}, Ω_{23} and Ω_{13}. The visual representations on the battery surface indicate its current charge level while those spaces fill completely during complete charging. The ground-state energized three-level system operates as a bare battery. A battery occupied by the orange state has partial charge according to our understanding. The battery reaches its maximum excited condition as a fully charged state at this level (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the system becomes typical in large Hilbert spaces under unitary evolution of H(t) against a fixed measurement Hamiltonian H_0. A model demonstrates how quantum systems feature within high-dimensional Hilbert spaces create dependable and stable energy dynamics that exist in random initial states and random Hamiltonians and random evolution operators. RQB setup works with finite Hilbert space which contains an initial state ρ while the system follows unitary evolution under the time-dependent Hamiltonian H(t). Mathematically the unitary time evolution operator takes the following form [80]:

$$U(t) = T\, exp\left(-i\int_0^t H(s)\mathrm{d}s\right)$$

where T denotes time ordering. The battery stores its energy from a well-defined measurement Hamiltonian H_0 and the extracted work emerges as changes in energy relative to this reference framework.

Randomness occurs throughout the model using either the initial state ρ or the measurement Hamiltonian H_0 or the evolution operator U (t) when implemented with random rotations that preserve the system spectral properties. The research shows that the extracted work in large n-dimensional systems becomes typical for all specific cases because its outcome mainly depends on system spectral properties alongside driving characteristics. Spectral structure together with coherence act as storage resources according to the RQB model. No work can develop from the system unless its initial state is incompatible with both the time-evolution operator and measurement Hamiltonian which provides direct evidence for coherence and quantum correlations. The connection between the behavior of batteries and quantum chaos is a profound one because these phenomena are associated with measurements recorded using out-of-time-order correlators (OTOCs) [80].

The model provides viable analytical understandings that are equivalent to the Jaynes-Cummings model [80] in perturbation but has certain restrictions on computational capabilities. Unless elaborate spectral characteristics are applied, quantum efficiency degrades at $n \to \infty$ as thermodynamic limit. There is no concept of both dissipative effects and environmental de-coherence in the model though the two are critical in the practical implementation of the model. The RQB framework presents a strong statistical tool that explores high-dimensional quantum energy dynamics while enabling new research on information scrambling and chaotic systems as well as thermodynamic irreversibility [80].

5. Recent advances on QB

Recently QB have been realized more quickly, and ambitious theoretical models have been proposed, which are conscious of realistic dissipation, variability of fabrication and benchmarking considerations. Notably, there have been advances in charging rates in molecular microcavity systems, designed driving regimes in superconducting platforms, reservoir- and nonreciprocity-based approaches to stabilizing the dark-state, and demonstrated proof of battery performance on photonic platforms. Recent advancement in QB model is shown as following:

5.1. Experiments on organic microcavity / super-absorption

Collected super absorption and ultrafast charging dynamics in ultrasonic optical experiments in molecular microcavities at a time resolution of femtoseconds have shown that environmental decoherence can be relevant in stabilization of stored excitation and facilitation of metastable trapping in sub radiant manifolds. These experiments relate light-matter polaritonic physics to the concepts of QB and suggest that excitation energy can be taken up in suitably engineered microcavities on a timescale of femtoseconds [32].

5.2. *Superconducting / transmon protocols with frequency-modulated driving*

Experiments with superconducting circuit platforms demonstrated that, with an appropriate design of frequency-modulated driving (STIRAP-style or similar protocols) charging/discharging efficiency in transmon-based devices can be significantly enhanced, and therefore circuit-QED is an attractive near-term testbed to experiment with QB concepts [46].

5.3. *Reservoir engineering & nonreciprocal devices for dark-state protection*

Theoretical and experimental suggestions to apply nonreciprocal reservoirs and reservoir engineering have shown the suppressed radiative losses and enhanced storage lifetimes through the stabilization of dark/sub radiant manifolds - in certain instances with order-of-magnitude increases in the amount of stored energy in model systems. These schemes fill the gap between the abstract dark-state proposals of photonic/electronic architectures [76].

5.4. *Optical-platform experimental verifications of capacity and metrics*

More recent optical experiments have started to measure and confirm QB capacity measures (definitions of ergotropy, and similar capacities) in few-photon systems, to understand the tradeoffs between coherence, entanglement and extractable work in real systems. These studies offer quantitative paths to the benchmarking of QB performance and make realistic LCSE / cost comparisons [64].

Overall, these developments demonstrate improvements in three areas: (i) high-speed charging and polaritonic/molecular systems that implement the super absorption concept; (ii) active control and driving schemes in solid-state superconducting systems that enhance charging efficiency and ergotropy extraction; and (iii) reservoir and non-reciprocity engineering that give plausible ways of securing stored energy. Nevertheless, scaled energy densities are small and reproducibility / manufacturing tolerances are now a significant bottleneck to scale to practical energy-storage usage.

6. Experimental realizations and prototypes

6.1. *Superconducting quantum batteries*

The Elizabeth et al. proposal demonstrates a superconducting QB (SQB) design which uses two capacitive connected superconducting charge qubits known as transmon qubits as its foundation as shown in Fig. 7 [81]. Superconducting circuits which contain Josephson junctions create artificial atoms with fixed energy states that represent the core element in present-day quantum computing systems because they display moderate sensitivity to charge noise. The qubits participate in coherent energy exchange interactions by connecting to a fixed capacitor. Operating the system at the degeneracy point allows researchers to reduce de-coherence effects from charge fluctuations by fixing the normalized gate charges at This operational mode strongly reduces low frequency noise and enhances system coherence [81].

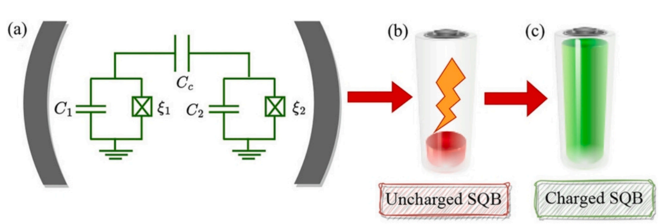

Fig. 7. The schematic system representation illustrates the proposed SQB charging protocol. The initial state of the system consists of two superconducting qubits at thermal equilibrium when the system is prepared according to a) Gibbs state. The two Josephson junctions function as qubits which serve as representations of the first and second Cooper pair boxes. The necessary energy for SQB charging comes through a local field pulse application. Panels b) illustrate the battery in an uncharged state while panel c) shows the battery in its charged condition. Reprinted from S. Elghaayda, *A. Ali*, S. Al-Kuwari, A. Czerwinski, M. Mansour, *S. Haddadi, Adv. Quantum Technol.*, 2025, © 2025 The Author(s). Published by Wiley-VCH GmbH under the terms of the Creative Commons Attribution License (CC BY).

A derivation of the degeneracy-point battery Hamiltonian starts from general charge qubit theory leading to simplified terms which describe Josephson tunneling and mutual interactions as shown in eq. 18 [81,82]:

$$H_B = -\frac{1}{2}\left(\xi_1\sigma_x^{(1)} + \xi_2\sigma_x^{(2)} - \xi_c\sigma_z^{(1)}\sigma_z^{(2)}\right) \tag{18}$$

The system consists of two Josephson energies for the first ξ_1 and second ξ_2 qubits together with ξ_c overlapping system energy. At the natural level the Pauli operators $\sigma_x^{(1)}$ and $\sigma_z^{(1)}$ translate to conventional spin-flip operators and population difference operators that operate on independent qubits. The internal energy dynamics of the SQB are described by this Hamiltonian which remains essential throughout the battery's charging and discharging processes.

Realistic operating conditions emerge when the authors define the initial state by using a Gibbs state at finite temperature instead of the ground state. This assumption establishes a practical link between theoretical work and existing superconducting circuit experimental conditions since absolute zero is theoretically unobtainable. The thermal initial condition appears as eq. 19 [82,83]:

$$p_{\text{th}}\,(0) = \frac{\mathrm{e}^{-\beta H_B}}{\mathrm{z}}, \beta = \frac{1}{\mathrm{T}}, Z = Tr\left(\mathrm{e}^{-\beta H_B}\right) \tag{19}$$

The temperature value of the thermal reservoir is denoted by T. The battery enters this state before charging begins with no applied charge. The charging process uses a unitary transformation generated from a time-varying driving field applied in the x direction. The external field operates as an artificial microwave pulse which performs state transitions in qubits while it introduces energy to the system. During the charging process the control Hamiltonian is (eq. 20) [81,82]:

$$\mathrm{H_{cx}} = \Omega(\mathrm{t})(\sigma_x \otimes \mathrm{I} + \mathrm{I} \otimes \sigma_x) \tag{20}$$

The model (eqs. 18–21) will have two identical transmon qubits, which are capacitively coupled Josephson junctions coupled and driven by microwave pulses. There are also boundary conditions; that is, zero-temperature or finite thermal Gibbs initial states and an isolated system when charging. There are limitations such as the possibility of neglecting flux noise, gate errors and qubit relaxation and hence the performance estimates are ideal upper bounds.

The Pauli X operations influence each qubit while Ω(t) represents the drive amplitude during this operation. During this charging process the battery undergoes unitary evolution described through the operator U(t) as eq. 21 [81,82]:

$$U_x(t) = exp(-iH_{CX}t), t = \Omega t \tag{21}$$

The system's energy levels transition due to this operator which completes the charging process. The evolution occurs in a sealed system without de-coherence or dissipation during the charging procedure establishing a theoretical base for the perfect battery operation.

This model efficiently reproduces important characteristics of coherent quantum charging but declares specific simplifying assumptions. De-coherence mechanisms including relaxation effects and flux noise alongside gate imperfections are absent from the model although they naturally occur in operating superconducting systems. The performance estimates therefore represent upper bounds rather than achievable averages under laboratory conditions. Symmetrical qubits are relied on in the analysis and may be difficult to uphold during the fabrication process. This approach provides a solid base to comprehend the functions of quantum coherence together with system symmetry and coupling mechanisms in superconducting QB operations [81,82].

6.2. STIRAP-based stable batteries

The study by Santos et al. introduces a design of QB system based on a three-level system (qutrit) with STIRAP technology to store the energy in a stable form over prolonged periods of time [34]. The model ensures the existence of strong energy storage through the established Stimulated Raman Adiabatic Passage (STIRAP) methodology [34]. The Hamiltonian of the battery system consists of the basic energy states $|\varepsilon_1\rangle$, $|\varepsilon_2\rangle$, $|\varepsilon_3\rangle$ that connect through external driving fields with the Rabi frequencies $\Omega_{12}(t)$ and $\Omega_{23}(t)$. Population transfer using dark state $|E_0(t)\rangle$ enables stable charging without switching off the driving fields because the process maintains stable population in the excited state. The extractable work achieves its maximum $C_{max} = \hbar(\omega_3 - \omega_1)$ at complete system excitation to $|\varepsilon_3\rangle$ (Fig. 8) [36].

The proposed battery consists of a qutrit with energy eigenstates $\{|\varepsilon_1\rangle, |\varepsilon_2\rangle, |\varepsilon_3\rangle\}$, governed by the Hamiltonian as eq. 22 [36]:

$$H_0 = \sum_{n=1}^{3} \varepsilon_n |\varepsilon_n\rangle\langle\varepsilon_n| \tag{22}$$

The combination of tunable resonant fields with their corresponding Rabi frequencies $\Omega_{12}(t)$ and $\Omega_{23}(t)$ forms the interaction Hamiltonian $H_t(t)$ that enables the controlled energy coupling between levels during the charging process. The main advantage arises from using the dark state $|E_0(t)\rangle$ to transfer populations adiabatically thus preventing $|\varepsilon_2\rangle$ state involvement. The dark state evolves as eq. 23 [36]:

$$|E_0(t)\rangle = \frac{\Omega_{23}(t)}{\Delta(t)}|\varepsilon_2\rangle - \frac{\Omega_{12}(t)}{\Delta(t)}|\varepsilon_3\rangle \tag{23}$$

This model (eqs. 22–23) presumes a three-level system given a closed system which is driven by coherent fields in adiabatic conditions. Boundary conditions presuppose that the system is in the ground state and does not have noise. The conditions are that driving fields are perfectly timed, and perfectly controlled in phase. The basic charge of restrictions includes the maximum charging velocity of the adiabatic condition, high sensitivity to decoherence or timing errors that makes experimental implementation difficult. The Lindblad master equation allows the analysis of open quantum system effects while proving resistance to moderate relaxation rates of $(\Gamma_{21}, \Gamma_{32})$ and dephasing rates (γ_2, γ_3). The three-level design allows spectral engineering for self-discharge suppression although two-level systems lack this capability. Researchers propose using superconducting transmon qutrits for experimental work because they offer both a harmonically tunable spectrum and microwave control capability.

This research demonstrates that superconducting transmon qutrits represent an experimental strong candidate because they provide both adjustable an harmonicity characteristics and microwave-based gate capabilities. STIRAP requires transmon structures because they support the required energy levels through circuit quantum electrodynamics fabrication standards (Fig. 9) [36].

Several key internal limitations exist in this model: (1) the adiabatic condition sets a fundamental speed limit for charging and reduces power output capacity, (2) while weak types of noise are handled well yet strong de-coherence causes performance degradation and precise control of time-dependent couplings becomes necessary for practical scalability. (3) The theoretical models must be improved by developing shortcut techniques of adiabaticity and error-free designs to enable the scientists to transform theoretical ideas into experiments [36].

6.3. Josephson phase batteries

The Josephson phase battery [83] is a radical quantum technological breakthrough that allows a continuous delivery of phase bias to superconducting networks where voltage biases are delivered by conventional batteries. The implementation of the device is based on a hybrid platform consisting of an n-doped nano-wire of InAs having unpaired-spin surface states attached to Al superconducting leads as illustrated in Fig. 10. The primary innovation is the anomalous Josephson effect which achieves φ_0 phase bias due to the presence of SOC and exchange interaction (interacting to break time reversal symmetry and inversion symmetry) [83].

The Josephson current-phase relationship (CPR) in such a system is given by eq. 24 [84]:

$$I_J(\varphi) = I_c \sin(\varphi + \varphi_0) \tag{24}$$

where I_C is the critical current, φ_0 is the anomalous phase shift. And φ is the phase difference across the junction, and this φ_0 junction behavior arises from the Lifshitz invariant in the free energy as eq. 25 [84]:

$$F_L \sim f(\alpha, h)(n_h \times \hat{z})\cdot v_s \tag{25}$$

The expression contains three elements: α as Rashba SOC coefficient [84] while h represents exchange or Zeeman field strength and n_h defines the field direction and v_s refers to superfluid velocity. This model (eqs. 24–25) refers to the aberrant current-phase correlation in an InAs nanowire by means of Al superconducting leads under spin-orbit connection and exchange field. Cryogenic temperatures and clean interfaces are necessary as well as an in-plane magnetic field, as part of the boundary conditions. It presupposes the high spin-orbit interaction and ferromagnetically ordered spins on the surface. Limitations are extreme sensitivity to magnetic noise, material disorder and device-to-device variation.

The device utilizes an InAs nanowire which is located between two Al superconducting electrodes. An in plane magnetic field B_y polarizes the unpaired spins which reside on the nanowire surface thus creating the persistent phase bias φ_0. The phase bias here shows adjustable behavior since spins within an area exhibit ferromagnetic coupling

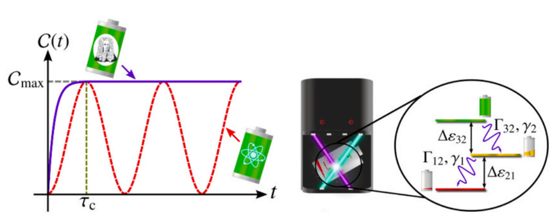

Fig. 8. (a) The schematic shows stored electrical energy in classical and QB systems. The charge state of classical batteries reaches stability after time τ_c but QBs show alternating charges during operation. (b) The three-level QB together with its resonant-based charger. The charging process takes place through individual energy steps with a gap size of $\Delta\varepsilon_{nm} = \varepsilon_n - \varepsilon_m$ between each level. This figure is adapted/ reproduced/reprinted from ref. 36 with permission from American physics society, copyright 2019.

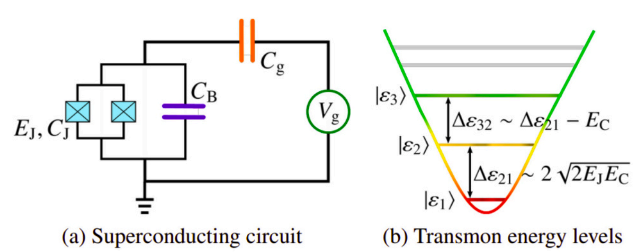

Fig. 9. (a)The image shows the superconducting transmon qubit circuit with its essential elements that link a Josephson junction of capacitance C_J to a large capacitance C_B. (b) The maximum stored energy of the transmon qutrit emerges from the E_J and E_C energy values. This figure is adapted/ reproduced/reprinted from ref. 36 with permission from American physics society, copyright 2019.

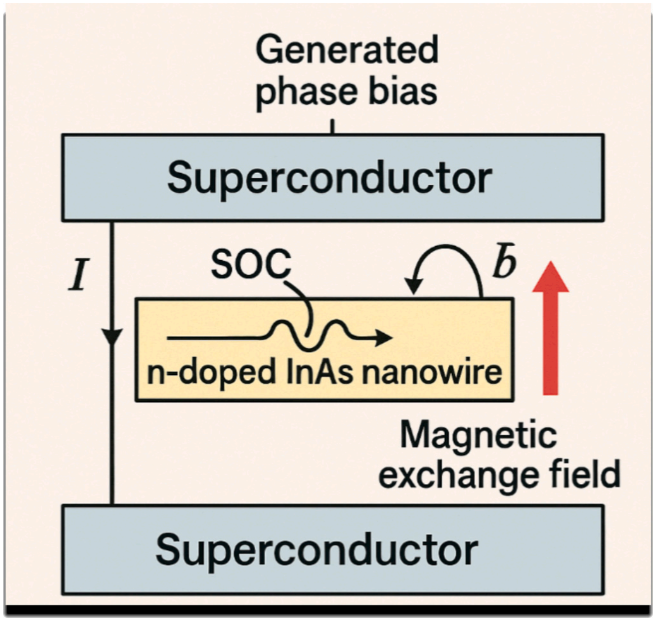

Fig. 10. A schematic diagram of Josephson phase battery.

which produces hysteresis effects [84].

This phase battery achieves several notable experimental results during its implementation. The phase bias of this device causes hysteresis effects in response to tuning by an in-plane magnetic field while exhibiting symmetric odd behavior during field switches and reaching $\pi/2$ at elevated field strengths. The system has two such phase effects that are shifts caused by the magnetic fields as well as phase biases caused by the unpaired Ferro magnetically ordered spins. The maximum phase shift is attained when the magnetic field is perpendicular to the axis of the nanowire since it shows that spin-orbit coupling is important. The subsequent experiments on other apparatuses indicate that the effects are repeatable but disparate specimens have dissimilar strength of measurement. The effects on quantum computing and superconducting electronics are far-reaching due to these technological innovations. The phase battery can precisely control phases in flux qubits and hybrid quantum systems, and acts as a multiple phase tuning in quantum memory storage elements and assists in the progress of topological quantum systems [82–84].

6.4. Room temperature QB

The development of a functioning QB system that can work at room temperature was achieved by the experimental researchers, thus a significant breakthrough in the study of quantum energy storage. A milestone in the experimental scientists was achieved to perform the complete QB operation that combines these key features super extensive charging and quantum collective effects, energy storage through spin-state methods, and efficient electrical energy recovery. The system has accurately shaped Fabry-Perot micro cavity structures that encapsulate copper phthalocyanine (CuPc) molecules as quantum absorbers [85]. This high level of interaction between light and matter allows creating hybrid states referred to as polaritons that propel the remarkable action of the battery.

N molecules in the charging mechanism interface with super absorption by collective quantum interaction with electromagnetic fields that can be effectively coupled with a strength proportional to $\sqrt{N}$. The fundamental design gives rise to two quantum benefits that create super extensive scaling of overpowering density and sub extensive time decrease that makes larger batteries charge significantly quicker than not anticipated by conventional considerations. The quantum mechanics working was experimentally demonstrated through CuPc molecular devices of 2.8×10^{14} to 7.9×10^{14} molecules that gave femtosecond charging times with power densities which had non-linear correlations to the molecular concentration. The new design introduces the use of two-state energy storage that is its key innovation. Singlet excitons (S_1) were produced by polariton creation and intersystem crossing between them to triplet species (T_1) was rapid (about 200 fs) due to spin-orbit interactions at copper centers in CuPc [86].

This unstable transition of the device generates long shelf life due to the fact that triplets' self-preserve tens of nanoseconds and this is six orders longer than the charging period duration. Such metastable states form the basis of practical energy storage to solve a significant technical problem researchers encountered in building earlier QB models. Specialized blocking layer, together with charge transport layers (CuPc/C_{60}) are employed in a hetero structure device to create an energy gradient so as to maximize efficient charge separation and limit recombination loss. The device exhibited dramatic external quantum efficiency growth as well as huge power variation rate when the system scale increased based on electrical assessments compared to regular devices without a cavity control setup. The QB configuration dominated classical systems when measured under optimal bias points according to current-voltage tests (Fig. 11) [86].

The experimental theoretical foundation combines Tavis Cummings models [46] regarding collective light-matter phenomena with Lindblad master equations that model dissipative processes [86]. Details from the complete model demonstrate accuracy when comparing it to actual experimental scaling relations and temporal processes which include a rate of cavity loss ($\kappa \approx 33$ ps^{-1}) and singlet relaxation rate ($\gamma^{-} \approx 0.5$ ps^{-1}) as well as intersystem crossing rate ($\gamma_ISC \approx 5$ ps^{-1}). Computer simulated results for the energy dynamics together with differential reflectivity demonstrations match experimental findings throughout all tested configurations.

Multiple implementation obstacles need to be resolved before practical application can progress despite the obtained breakthrough. Despite being high for quantum devices, the present energy density remains unable to match conventional electrochemical cell capabilities. The fabrication control precision needs improvement because device to device variations occur in cavity tuning together with molecular density fluctuations [86].

6.5. Cavity-mediated quantum systems

Hadipour et al. have introduced a functional QB model using an atom and cavity system attached to a special bosonic reservoir [87]. The scheme features the QB (QB) as a qubit shown in Fig. 12 and it uses the cavity to separate the QB from any environmental impact that could cause decoherence. When this is assembled, it is possible to deliver energy to the QB through the cavity within a certain interval $[0,\tau)$. In the range $(0,\tau)$, the state of the system is regulated by a switching function $f(t)$, where $f(t) = 1$. Charging makes $f(t)$ equal to 1. $f(t) = 0$ otherwise. In classical mechanics, the Hamiltonian that describes the movement is shown in eq. 26 [87]:

$$H = H_0 + f(t)\, H_I \tag{26}$$

This model (eqs. 26–31) supposes that a qubit is interacting with a cavity that is interacting with a structured bosonic reservoir. Boundary conditions were based on non-Markovian dynamics and Lorentzian spectral density of a system and initial ground state. It is based on weak coupling between the cavity and the environment and strong memory effects. Its disadvantages are that it is extremely sensitive to cavity losses, that it requires very fine spectral engineering, and that it is experimentally difficult to control both memory times and couplings at the same time.

where the free Hamiltonian H_0 and interaction term H_I are respectively (eqs. 27 & 28) [86]:

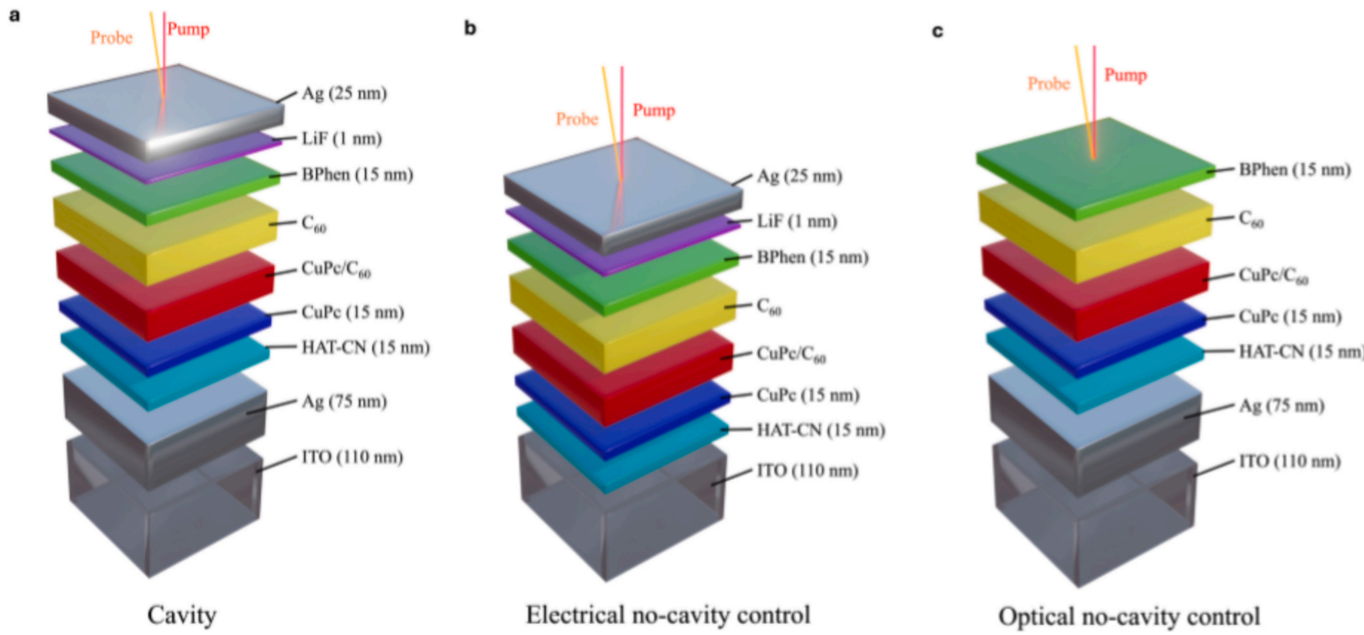

Fig. 11. The diagram shows how the QB is arranged in layers to exhibit its working principles, composition of each component. The device extracts charge using pulses from ultrashort laser tools and probes its performance using more ultrashort laser elements. Figure reproduced (or adapted) from ref. 86 licensed under Creative Commons Attribution 4.0 International (CC BY 4.0).

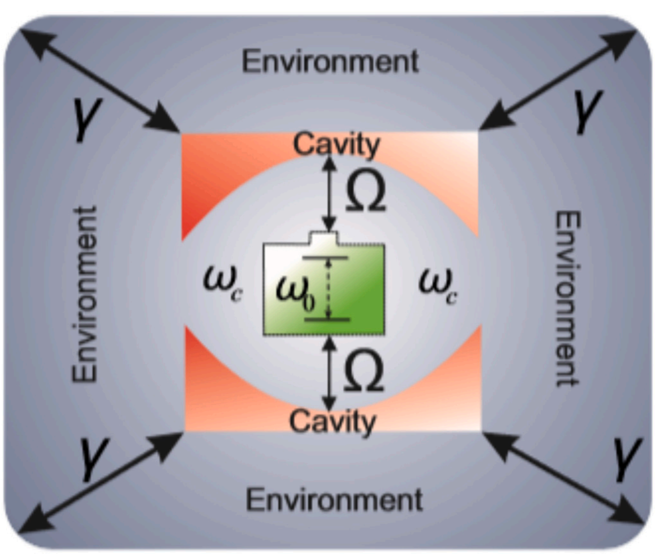

Fig. 12. Visual set up of cavity mediated QB [87]. [Reprinted from M. Hadipour et al., *Practical Scheme for Realization of a QB*, arXiv:2312.06389 (2023), CC BY 4.0].

$$H_0 = w_0\sigma^+\sigma^- + w_c a^+ a^- + \sum_k w_k b_k^+ b_k \quad (27)$$

$$H_I = \Omega\left(\sigma^+ a + \sigma^- a^+\right) + w_c a^+ a^- + \sum_k g_k\left(a b_k^+ + a^+ b_k\right) \quad (28)$$

Here, Ω is the coupling strength between the battery and cavity, and g_k denotes the cavity-environment coupling.

The design works especially well in places that display memory effects. If the environment is modeled by using a Lorentzian, spectral density is shown in eq. 29 [87]:

$$J(\omega) = \frac{\gamma\lambda^2}{2\pi\left((w_0 - w)^2 + \lambda^2\right)} \quad (29)$$

λ^{-1} defines environmental memory time. When the environment is treated as non-Markovian, it lets energy flow back from the system which increases battery charging. The new state of the battery is determined with Laplace transforms and the reduced density matrix created after charging finishes τ is (eq. 30) [87]:

$$\rho_B(\tau) = |c_2(\tau)|^2|e\rangle\langle e| + \left(1 - |c_2(\tau)|^2\right)|g\rangle\langle g| \quad (30)$$

The stored energy is shown in eq. 30 [87]:

$$\Delta E_B(\tau) = \omega_0|c_2(\tau)|^2 \quad (31)$$

Breuer–Laine–Piilo (BLP) method has used to quantify non-Markovianity N, defined via the trace distance between two evolving states. As shown in Fig. 13, the degree of non-Markovianity increases with stronger QB–cavity coupling Ω and longer environmental memory

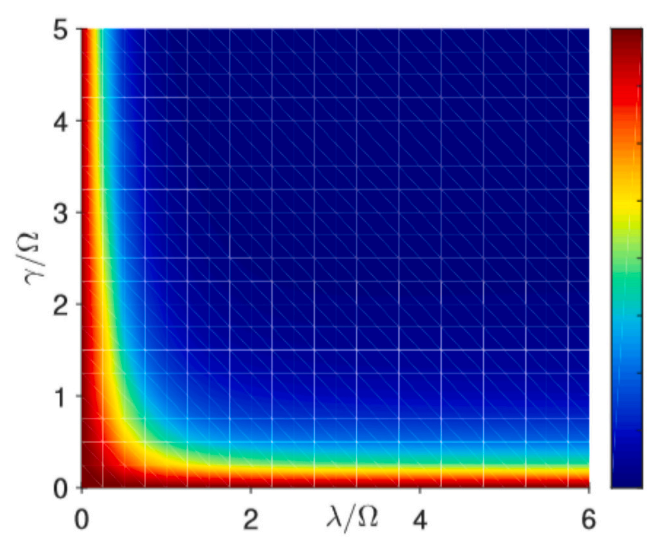

Fig. 13. Non-Markovianity N, function of λ/Ω & γ/Ω [85]. [Reprinted from M. Hadipour et al., *Practical Scheme for Realization of a QB*, arXiv:2312.06389 (2023), CC BY 4.0].

(i.e., smaller λ), but decreases with increasing cavity–environment coupling γ.

Further numerical analysis demonstrates that the maximum stored energy ΔE_{Bmax} and ergotropy Wmax are significantly enhanced in the non-Markovian regime. For example, Fig. 14 shows the dependence of both quantities on γ/Ω and λ/Ω, illustrating that optimal charging occurs for strong battery–cavity coupling and weak cavity–environment coupling, especially when the environment has memory.

6.6. Ultra-cold atom QB

Ultra cold atoms in optical lattices can be used to test different quantum many-body models, including some used in the study of quantum batteries. They are flexible so that lattice structures, bonds between atoms and the system's dimensions can be precisely controlled. Use of optical lattices allows scientists to model the Hubbard, Heisenberg and Ising models which help in studying energy in highly linked quantum states [88].

It is very important to model non-equilibrium quantum dynamics, since this is key for the operation of quantum batteries. Tools such as quantum gas microscopes, Floquet engineering and synthetic gauge fields [89] can be used to reproduce processes like coherent exchange of energy, the spread of entanglement and such processes as dissipation in systems. For example, embodied in the Hubbard model is the key physics behind interacting fermions, Hamiltonian is shown in eq. 32:

$$H = \sum_{\langle i,j\rangle,\sigma} \left(c_{i\sigma}^{+} c_{j\sigma} + h.c\right) + U \sum_{i} n_{i\uparrow} n_{i\downarrow} \tag{32}$$

where the amplitude of the tunneling is t, U describes the strength of the interaction, and $c_{i\sigma}^{+}c_{j\sigma}$ are operators to create and eliminate spin-fermions on site i. This model assumes fermionic atoms in ultra-cold (nano- Kelvin) temperatures in an optical lattice. There is need to optical trap, thermal variations to be negligible and external fields isolated. It is applied to tight-binding approximation and an ideal lattice control. Its drawbacks are its technical complexity, large temperature requirements and sensitivity to trapping lasers which require high decoherence, and it is not feasible to achieve large scale energy storage.

This model facilitates the dynamics of many body interactions and spin dynamics which are important in quantum batteries. Optical lattices also allow scientists to investigate the SU(N)-symmetric systems [90–92] consisting of Yb and Sr two-electron atoms [93,94] that allowed to preserve and control better the quantum states. The fact that Feshbach resonances (magnetic, optical, orbital) allow scientists to fine-tune the strength of interactions can be used to determine the degree to which QBs can store energy and the extent of their coherent life [95].

7. Comparative analysis of QB

QBs have realized significant theoretical research attention because they are better performing charge storage units that take advantage of quantum resources such as coherence and entanglement along with collective behaviors. There are different physical systems as well as material that have been considered to implement QB by using two-level systems and complex cavity QED systems and spin chain setups. Every quantum storage platform delivers specific benefits alongside corresponding constraints in both storage capabilities and charging speed and experimental implementation as well as resistance to de-coherence effects [96–102]. The below comparative review presents Table 1 and Fig. 15 that outline major materials and relevant models related to QBs while detailing their benefits and drawbacks.

The trade-offs of the QBs exhibit qualitatively different behavior than the classical electrochemical cells. The most important benefits include faster charging (shorter charging time t) and great instantaneous charging power that occurs due to collective / correlated processes, and the possibility of miniaturization. As an example, Dicke-type cavity models can be used to predict collective amplification of charging power. Super extensive absorption has been reported in early studies on $\sqrt{N}$ scaling, and experiment with organic microcavities has found super extensive absorption which is consistent with charging pathways enhanced in the cavity [46]. Nevertheless, there are still a number of significant disadvantages: (i) it is sensitive to decoherence and environmental dissipation which may limit extractable work (ergotropy) and reduce practical storage times; (ii) it is complicated and has high engineering requirements; (iii) the extractable energy per unit is often limited by the transition energy of the underlying quantum system and system-level energy density is sensitivity to packing density and practical device design is critical. Notably, the scaling of quantum-speedups has been model-dependent and have been evaluated critically in the literature in recent years - some studies have seen apparent scaling due to the increased classical field strength instead of a true quantum advantage, whereas other studies have demonstrated how to increase speed and strength [96–103]. In order to describe these trade-offs explicit, we compared representative metrics (ergotropy E, charging time τ, charging power P = E/ τ, scaling exponent α in $P \propto N^{\alpha}$) and shown in Table 1 and Fig. 15.

8. Application of QBs

QBs(QBs) are conceived to be transformative across a diverse array of new quantum technologies, through the provision of controllable, fast and miniaturized energy storage. They have special promise in the powering of Quantum computers, where the high-speed delivery of

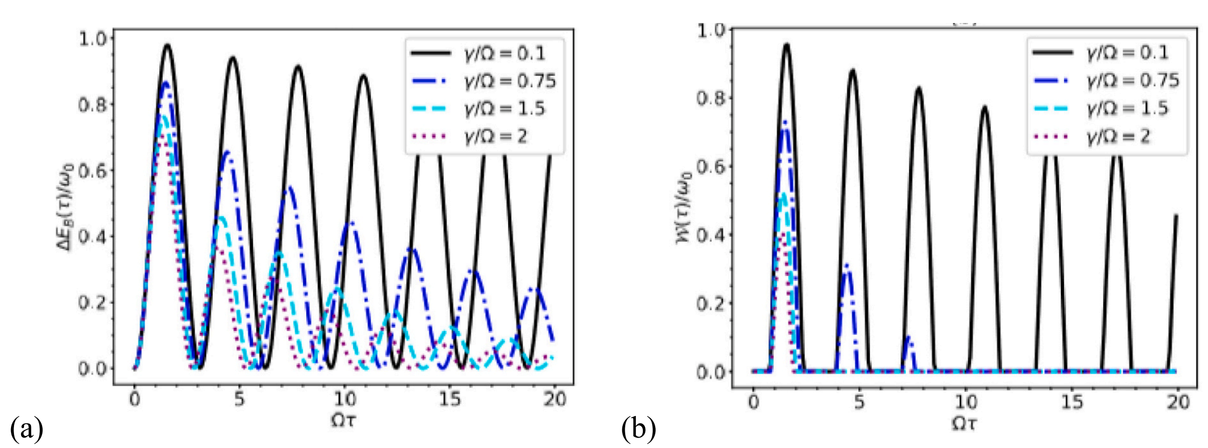

Fig. 14. (a) The changes in stored charge energy and (b) ergotropy for a non-Markovian system with λ/Ω = 0.1 are shown (for several values of γ/℡) during the charging process [85]. [Reprinted from M. Hadipour et al., *Practical Scheme for Realization of a QB*, arXiv:2312.06389 (2023), CC BY 4.0].

Table 1
Comparison between different quantum batteries.

Model	Physical implementation	Typical energy per elementary unit (order)	Charging-power scaling with N (reported)	Experimental readiness	Vulnerability to decoherence / primary disadvantage	Refs
Dicke / cavity QB	N TLS coupled to a single cavity mode	~ℏω per TLS (0.1–1 eV scale typical for optical/solid-state systems)	Claimed P∝ $\sqrt{N}$ (theoretical claim); interpretation debated (classical-field vs genuine quantum advantage).	Theory + suggested solid-state implementations; some experimental prototypes inspired by cavity QED	Strong sensitivity to radiative losses and cavity decay; extractable energy can be reduced by correlations.	[39]
Rabi / local chargers (parallel)	Each TLS charged independently	similar per unit	P∝N trivially (parallel), but no collective speedup per resource	Mostly theoretical / toy models	Less sensitive to collective decoherence, but no quantum speedup	[32]
Spin-chain / many-body QB	Interacting spin chains, solid-state spins	~ℏω per spin	Model-dependent: can show collective advantages for limited interaction-order	Theory, some model solid-state proposals	Decoherence, disorder, finite-size effects; scalability depends on engineered interactions	[97]
Organic microcavity (super absorption)	Molecular dyes in microcavity	excitonic energies (~1–3 eV)	Super extensive absorption observed (enhanced rate vs single molecules)	Experimental demonstration (2022) — proof of principle	Fast radiative losses; storage time short unless triplet / metastable engineering used	[46]
Charger-mediated / open QB (dephasing control)	Driven charger + battery, open system	model-dependent	Can achieve faster charging via optimized dephasing; increases robustness	Theory (2025) with concrete model numbers	Requires engineered noise/ dephasing control; realistic implementation complexity	[102]
Superconducting qubit implementations	Transmons, microwave cavities	microwave photon energies (μeV–meV) per excitation	Experimental steps toward collective charging; scaling limited by coherence times	Early experiments / proposals	T1/T2 limit storage time; require cryogenic infrastructure	[101]

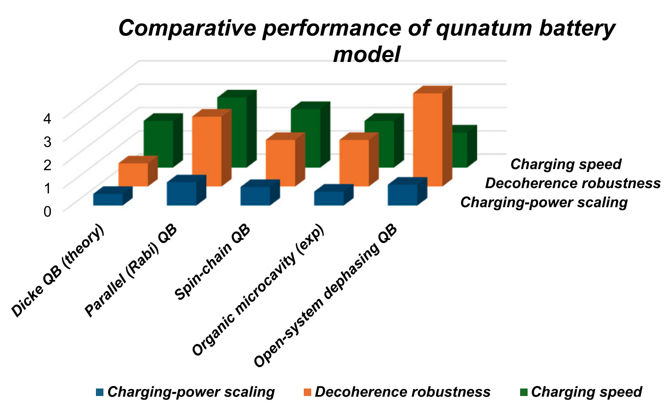

Fig. 15. Comparative performance of QB model.

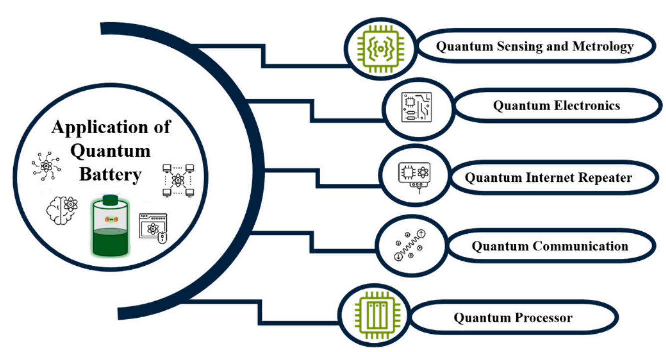

Fig. 16. Applications of QB.

energy is critical to propelling superconducting qubits as part of the computation cycles. QBs can be used as nodes of energy in photonic links in Quantum communication networks, and permit low-loss and high-speed data communication between remote quantum devices. Their small size (nanoscale) ensures that they are applicable in wireless implanted biosensors and other nano-sized medical sensors in which the traditional sources of energy are too large or slow to be recharged. QBs also are suggested to serve as onboard energy units of space micro-robots and remote Internet of Things (IoT) quantum nodes, which need long-duration energy storage with no physical recharge. Also, they may provide rapid bursts of energy to Quantum artificial intelligence accelerators and Quantum metrology devices to operate ultra-precise clocks, sensors, and quantum cryptography devices in secure communications. These various applications indicate the capability of QBsas enabling elements in the future quantum technologies as depicted in Fig. 16.

There is also recent work that has begun benchmarking superconducting QBs with the idealized theory physics. For instance, a capacitive breaker superconducting flux qubit made was experimentally demonstrated, in which the counter-diabatic charging using stimulated Raman adiabatic passage demonstrated stable charging near the quantum speed limit, but was limited to its performance by factors such as field strength and decoherence [47,103,104]. Not only did these results confirm fast and controllable charge, but they displayed implicit self-discharge and power stability-power trade-offs. It was then generalized to complementary circuit-QED system with resonator and qubit decay channels, which qualitatively estimated the ability to suppress oscillations and total effectiveness respectively, and provided design advice on how to create stable transmon-based batteries [101]. The aggregate outcomes of those studies are the first step in the creation of realistic superconducting QBs and prove the advantages of collective charging, yet indicate the problems of decoherence and resource overheads.

9. Economic modeling of quantum batteries

Although significant advances have been made in enhancing energy density and the multifunctionality of QBs through theoretical and experimental frameworks of investigation, the economic potential of QBs is in need of a general overview in order to become a viable commercial resource. In contrast to the conventional electrochemical systems to store energy, QBs are more conceived to be niche, high-power, low-energy applications owing to their merits e.g. to do ultrafast buffering of cryogenic Transmon qubit processors. This renders the traditional cost indicators such as the cost/kWh ineffective unless it is modified to the specific operation regime of QBs. Two economic models have been put forward to assess their feasibility; the leveled cost of stored energy (LCSE) and a throughput model of value [105,106]. The LCSE, defined in eq. (33), is a parameter that determines the cost of the extractable energy needed to supply one unit of energy per second of a device during its lifetime.

$$LCSE = \frac{C_{cap} + C_{O\&M}}{E_{usable.life}} \tag{33}$$

where is C_{cap} capital cost (device fabrication + integration), $C_{O\&M}$ is operational and maintenance cost, and the total extractable work (ergotropy) delivered is shown in eq. (34) [32,107]:

$$E_{usable.life} = N_{cycles} \times E_{ergotropy.cycle} \tag{34}$$

The QBs have a number of unique benefits over classical electrochemical cells. The notable one is their potential of quick charging using collective quantum efficiencies like entanglement or super absorption which can theoretically lower the charging time by orders of magnitude regarding ion diffusion-limited reactions in lithium-ion or magnesium-ion cells. Moreover, the energy unit quantum is also determined by transition frequencies that may be in the optical or microwave frequency windows, which promise miniaturized and multi-purpose architecture at the interface to quantum technologies. QBs can also in principle have high instantaneous power densities, which have been experimentally demonstrated in cavity-based Dicke models and in proof-of-principle organic microcavity experiments, in which improved absorption rates have been measured. These benefits are however offset by several shortcomings. First, the absolute energy density in a system is quite extremely low, even compared to those of electrochemical batteries. Second, QBs demand extremely specialized equipment, such as cryogenic systems to support superconducting qubits, optimal or microwave cavity systems, or trapped-ion systems of high purity, all of which are costly and complex. Lastly, the weakness of coherence and entanglement under decoherence hinders real life implementation, in most real-world systems decoherence times are only longer than realistic charging times, and unless there are error-correcting or error-tolerant schemes useful energy extraction is still a challenge. Simply stated, QBs are also superior in terms of charging speed, power density, and versatility in quantum technologies, but way behind the conventional batteries, in terms of energy density, cost efficiency, and large-scalability [32,39,96–103].

10. Future directions and research challenges

QBs exist as mostly theoretical concepts yet prove to be promising candidates in enhancing the storage capabilities of quantum technology. The future of QB development ought to focus heavily on the development of experimental realizations via platforms that have both superconducting circuits and trapped ions and spin systems. The application of various many-body quantum effects other than entanglement and coherence is promising to the operation speed of the charging process and energy storage capacity when used on systems with correlation effects such as spin chains and cavity-QED systems. Although theoretical and experimental developments in the field of QB have risen swiftly, there are few important obstacles that tend to prevent their implementation as laboratory prototypes and deployable energy storage systems. The issues that are most urgent are associated with safety, cost of storage, and scalability.

10.1. . Safety and flammability risks

Collective super absorption is also demonstrated in many QB platforms based on organic molecular layers localized within optical microcavities of high-Q. These designs often have small-molecule semiconductors, polymeric transport layers, which are flammable, like organic light-emitting devices. These films can be subject to local photothermal damages or burning, when not properly encapsulated, under extreme ultrafast optical charging pulses. To illustrate this, J. Q. Quach et al. have stated that even the moderate heating conditions during the procedures of super absorption necessitated the use of thermal management to avoid the deterioration of the material. Transmon qubit array based cryogenic platforms (Dicke model implementations) are not chemically flammable, but still expose both cryogen-handling and quench risks, and run risk of electrical safety issues and vacuum breach [49]. In a bid to be safe, future QB devices will need incorporation of non-flammable encapsulates, best thermal spreaders, and standardized testing of high-power pulse before its deployment.

10.2. Storage cost barriers

Currently, all QBs produce extremely low energy per device (ergotropy per cycle), and must be produced through costly high-precision nanofabrication, and thus their LCSE is orders of magnitude expensive compared to conventional batteries. It has been suggested that existing QB prototypes can provide densities of ergotropy extremely lower than those of commercial LIBs and are, therefore, economically unrealistic unless needed in niche ultra-fast buffering devices [32]. It is going to take significant gains in the energy density and fabrication yield to overcome this cost barrier.

10.3. Scalability limitations

The collective charging and dark-state storage are just a few examples of many QB effects that depend on a very symmetric interaction between a large number of the same quantum units. Practically, this symmetry is broken by the device-to-device variability (inhomogeneous broadening, cavity detuning and fabrication defects), which worsen the performance of the QBs as they scale up. B. Ahmadi et al. made it clear that currently it is nanofabrication yield and uniformity that prohibit the scaling of the QBs beyond the proof-of-concept stage [76]. Additionally, the cryogenic platforms are not scalable (cooling power requires limits, wiring complexity, wafer scale) and room-temperature spin-based QBs (e.g. Nitrogen-vacancy center ensembles) are implanted and aligned in real-wafer scale processes that are not yet technology-mature [79,81].

The control of the de-coherence effects and environmental noise takes critical roles as the modern control procedures of the open quantum systems are used. Quantum energy storage research should consider new material platforms that involve 2D materials and engineered nanostructures and topological insulators since these platforms are likely to have low dissipation and high-level coherence. The development of passive networks will be crucial to future development of innovation in QBs but requires a standardized measurement criteria to steer the development of the experimental capabilities across the platforms. In the near future, the advancement of QB technologies will make them working elements employed in the devices that will be at the front of the development of quantum technology.

11. Conclusion and future recommendations

The QBs are a paradigm shift in energy storage where the coherence and entanglement are employed to store the energy in a way that the charging rates and energy densities are to exceed the classical limits. The concepts of quantum advantage have been demonstrated in theoretical models in the previous 10 years and experimental observations have demonstrated that quantum advantage can be utilized in practice: with superconducting transmons, organic microcavities, and NV centers. Much of this has led quantum plates to become more than just hypothetical propositions, and has allowed it to develop into a rapidly expanding research field with seemingly promising technology. But practical application of the same is difficult. Even more finer energy readout schemes still need to be improved, coherence still limits the useful charging time, and scalable architecture is yet to be demonstrated. The latter are not as urgent as engineering and translational problems: how to enhance the performance of QBs when subjected to realistic noise and dissipation, how to make QBs cheap, scalable and produced, how to provide safety checks and balances to enable quantum operations to be performed under a variety of conditions. Such are the issues that shape the future roadmap. The close collaboration between quantum physics and materials science and device engineering would allow further progress of this field. By having the ability to improve efficiency, affordability, and safety simultaneously, QBs will be able to convert the hypothetical instruments to the imminent parts of the future quantum processor, the communication network, and nanoscale devices. It is not only going to power the next generation of quantum technologies but, also, is going to change the concept of the energy storage itself.

In the upcoming study, the main emphasis should be placed on the enhancement of the quantum batteries efficiency. Quantum coherence and entanglement has a potent effect on charging mechanism and high-power output, and the face is that quantum states are reliant on thermal dissipation and environmental decoherence. Future research must consistently aim at concentrating on the generation of the quantum systems that remain non-interacting with the environment through the use of the new materials that can sustain quantum characteristics over longer durations. It is extremely important to come up with new charge/discharge protocols that would deal with the effects of decoherence in order to achieve the full realization of the highly efficient quantum devices.

In order to consider the commercial viability of the quantum batteries, the roadmap for reduction of cost and scalability should be taken into account. The expensive manufacturing and utilization of exotic materials restrict the current state of work to produce laboratory scale prototypes which should be addressed on priority to go the mass production for future. Hence, researchers should explore earth abundant and cost-effective materials along with realization of scalable fabrication methodologies. In this regard, the integration of modern techniques on engineering, nanostructures, production of high crystal quality materials is key in this regard. These can bring the cost of production of QBs down in order to enable the consumers for use those in electronics, vehicles, and grid level applications in energy storage.

The realization of QBs is strongly dependent on development of robust safety protocols along with operational stability. Considering the different fabrication and working of quantum batteries, in comparison to the classical batteries, their exclusive characteristics offer unique challenges. Hence, researchers should give due attention to design the QB systems which are able to monitor the quantum states in safe and predictable manner. It demands consistent theoretical and experimental efforts to establish a framework which can earn human confidence and trust while stepping toward this future technology.

CRediT authorship contribution statement

Bazgha Khadim: Writing – original draft, Formal analysis, Conceptualization. **Abdul Majid:** Writing – review & editing, Visualization, Supervision, Project administration. **Ayaulym Belgibayeva:** Writing – review & editing, Visualization, Validation. **Yongcheng Jin:** Writing – review & editing, Visualization, Validation. **Niyazi Bulut:** Writing – review & editing, Visualization, Validation. **Mohammad Alkhedher:** Writing – review & editing, Visualization, Validation.

Ethical approval

Not applicable.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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