Open Source Technology and Justice Transition in Sustainable Energy: A Survey

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Abstract

This survey paper explores the comprehensive framework of open-source technology, justice transition, the common batteries model, open-source supply chain management, sustainable energy, and European Union (EU) policy. It underscores the integration of open-source principles with sustainable energy initiatives, emphasizing transparency, fairness, and sustainability in technological development and energy transition. The survey outlines the pivotal role of open-source technology in fostering innovation and collaboration within sustainable energy systems, while justice transition ensures equitable strategies that protect vulnerable populations during energy transitions. The common batteries model is examined for its potential to enhance energy storage and distribution, supporting sustainable energy systems. Open-source supply chain management is highlighted for its role in promoting transparency and efficiency through blockchain and other technologies. The survey critically analyzes the EU's policy framework in shaping sustainable energy transitions, focusing on policies that support open-source technology, justice transition, and sustainable energy. Key findings indicate that integrating these themes within EU policy can foster innovation, environmental responsibility, and social justice. The paper concludes by suggesting future research directions and potential areas for policy development to enhance sustainable energy practices and technological advancements.

1 Introduction

1.1 Structure of the Survey

This survey is structured to provide a comprehensive examination of the intersection between open-source technology, justice transition, and sustainable energy within the European Union policy framework. The introduction highlights the significance of integrating open-source principles with sustainable energy initiatives, focusing on transparency, fairness, and sustainability in technological advancements and energy transitions.

The survey proceeds to define core concepts such as open-source technology, justice transition, the common batteries model, open-source supply chain management, and sustainable energy, establishing a foundational understanding necessary for exploring the interrelations of these themes and their relevance to EU policy.

Subsequent sections delve into thematic areas, particularly the role of open-source technology in energy transition, which is analyzed for its impact on innovation, transparency, and collaboration in developing sustainable energy solutions. The critical importance of justice transition is also examined, emphasizing policies and practices that promote social equity in energy access and distribution.

The common batteries model serves as a strategic framework for enhancing energy storage and distribution, with a detailed analysis of its potential to strengthen sustainable energy systems while minimizing environmental impacts. This section includes a systematic evaluation of various energy

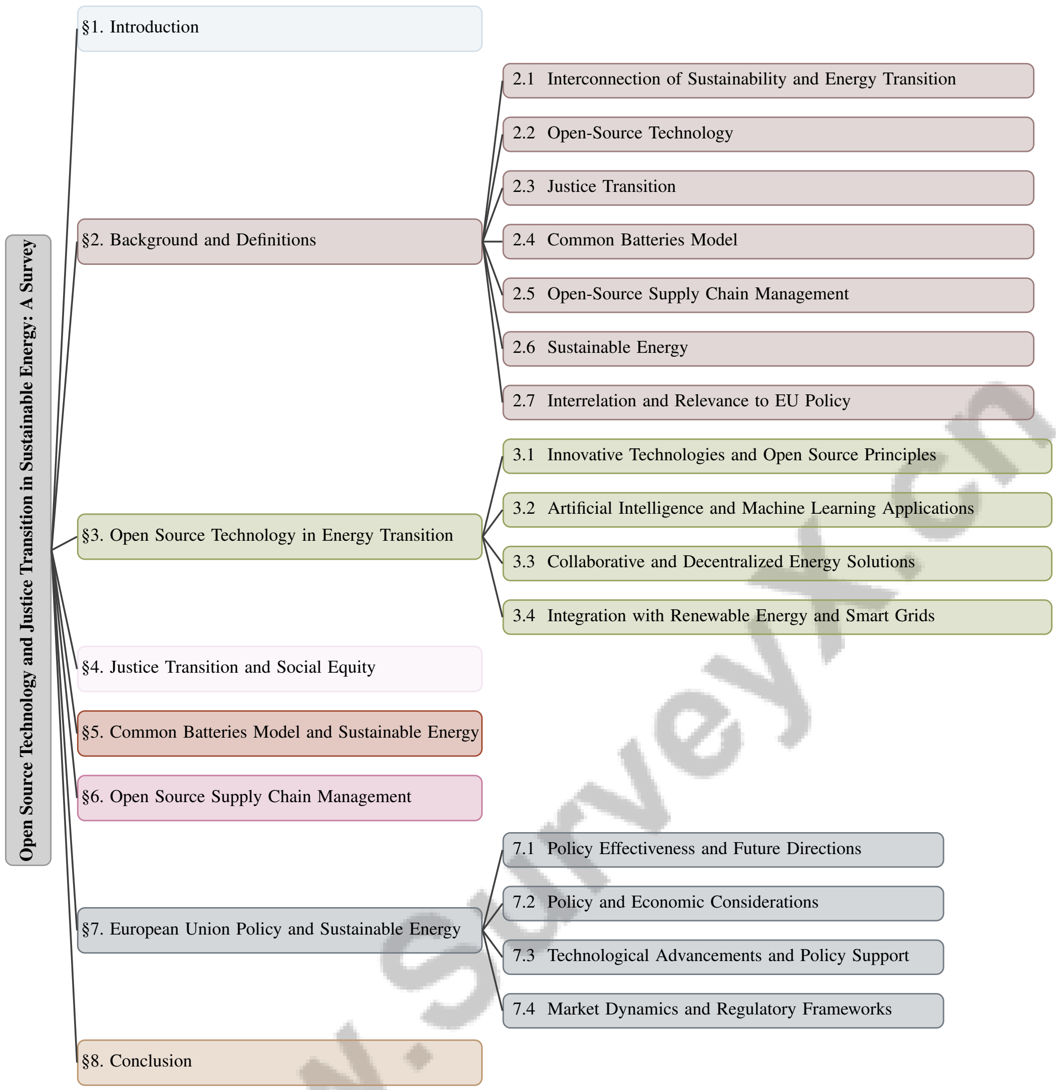

Figure 1: chapter structure

storage technologies, underscoring the importance of competition among them to optimize system costs and deployment configurations. By leveraging advanced technologies such as blockchain and artificial intelligence, the model addresses the complexities of managing distributed energy resources, contributing to the decarbonization of power systems and promoting sustainable energy practices [1, 2, 3, 4, 5]. The application of open-source principles in supply chain management for sustainable energy is also explored, highlighting how transparency and collaboration can enhance efficiency and sustainability.

The role of EU policy is critically analyzed, focusing on key regulations that support open-source technology, justice transition, and sustainable energy. The survey concludes by synthesizing principal findings regarding the drivers and barriers to concentrating solar power (CSP) deployment in the EU, emphasizing the need to integrate these themes into EU policy to improve renewable energy strategies. Future research directions are outlined, advocating for a comprehensive policy mix that promotes dispatchable technologies while mitigating administrative barriers, thereby fostering an environment conducive to CSP development and sustainable energy transition [6, 7, 8, 9, 10].The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Interconnection of Sustainability and Energy Transition

The integration of sustainability principles into energy transition and technological innovation is crucial for addressing the challenges of renewable energy adoption. The shift from fossil fuels to sustainable energy, especially in the transport sector, highlights significant obstacles [11]. This transition is further complicated by the complexities of energy planning in rural areas, where decision-makers must balance conflicting objectives to optimize energy alternatives [12].

Technological advancements, particularly in AI, enhance the efficiency and sustainability of energy systems. AI optimizes renewable technologies, with neural networks predicting ecological discharge in hydropower systems, promoting both ecosystem preservation and electricity production. Machine learning accelerates the development of energy solutions, facilitating the transition to renewable sources [13, 14, 15, 5]. Accurate forecasting of energy consumption, complicated by household characteristics and decentralized generation, is essential for balancing supply and demand [16].

The integration of sustainability principles into energy transitions involves a complex interplay of social, economic, and environmental factors, introducing uncertainties in energy management decisions. These efforts aim to mitigate greenhouse gas emissions and combat climate change, necessitating coordinated efforts across technological, economic, and social dimensions [17, 18, 19, 20, 5]. Addressing energy poverty and technological gaps, especially in regions like Sub-Saharan Africa, is critical for sustainable development.

The risk of high emissions resurgence post-pandemic and varying political commitment levels underscore the need for intelligent policies to transform potential setbacks into renewable energy growth opportunities. The direction of state support for economic recovery will be crucial in determining the pace and effectiveness of the shift towards a more sustainable energy system [21, 17, 18, 19].

2.2 Open-Source Technology

Open-source technology promotes collaborative and transparent development, democratizing energy solutions and accelerating advancements. It enhances privacy-preserving mechanisms like the w-PPSM, coordinating heat and electricity markets while safeguarding consumer data [22]. Open-source frameworks facilitate efficient communication in smart grids, with Automated Metering Infrastructure (AMI) improving operational efficiency [23].

Advanced energy solutions, such as tandem solar cells, benefit from open-source platforms that integrate machine learning and data mining, enabling rapid identification of materials with enhanced stability [24]. In electric and hybrid vehicle manufacturing, open-source technology enhances efficiency through AI integration [2]. Blockchain within the Energy Internet exemplifies managing distributed energy forms [4], while custom-built Hardware Performance Counters (HPCs) enhance microgrid security [25].

2.3 Justice Transition

Justice transition emphasizes equitable strategies ensuring all stakeholders, especially vulnerable populations, are not disproportionately affected by the shift to renewable energy. It addresses fairness in energy distribution, as seen in peer-to-peer energy cooperation frameworks [26]. Challenges like free-riders complicate justice transition, highlighting the need for robust strategies to ensure fair resource distribution [27].

Integrating Vehicle-to-Grid (V2G) technologies within Renewable Energy Communities (RECs) presents challenges due to ineffective strategies, leading to prosumer disengagement [28]. Addressing socio-economic dynamics and reorienting knowledge and power structures align with justice transition goals, democratizing energy access and empowering communities [29]. Sustained engagement and resource access are crucial for justice transition initiatives' continuity [30].

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2.4 Common Batteries Model

The common batteries model addresses efficient energy storage and distribution, crucial for renewable sources like solar and wind. Advancements in battery technologies, including all-solid-state batteries (ASSBs), enhance storage capabilities [31]. Accurate estimation of battery parameters ensures reliability and longevity, essential for optimal energy usage [32]. Integrating stochastic scheduling with demand response in microgrids emphasizes the model's importance [33].

Battery modeling methodologies, including first principles and machine learning, optimize performance [34]. These models enhance predictive accuracy, supporting efficient energy storage solutions. Batteries in variable speed wind turbines (VSWTs) illustrate their role in grid stability [35]. Exploring long-term storage solutions like underground hydrogen storage complements the model, offering pathways for clean energy resilience [36].

2.5 Open-Source Supply Chain Management

Open-source supply chain management (OSSCM) embodies transparency and collaboration, advancing sustainable energy systems. Blockchain integration enhances transparency and traceability [10], with IoT technologies enabling real-time data sharing [37]. Digital Twin (DT) technologies optimize decision-making and resource allocation in supply chains [38].

Advanced technologies like autonomous robots and big data analytics transform OSSCM, reducing inefficiencies and environmental impact [39]. Open-source models underscore governance and control of knowledge within supply chains [29]. Effective relationship management builds trust and cooperation, enhancing supply chain sustainability [40].

2.6 Sustainable Energy

Sustainable energy meets present needs without compromising future generations' ability to meet theirs, integrating renewable sources and minimizing emissions [13]. The EU aims for carbon neutrality by 2050, aligning with global initiatives like the UN SDGs. Technological advancements enhance energy efficiency and integration, with Distributed Energy Resources (DERs) increasing grid flexibility [16].

Evaluating carbon emissions is essential for developing management strategies aligning with sustainability goals. AI enhances precision in evaluations, facilitating informed energy management [6, 19, 9, 41, 5]. The EU emphasizes secure operations in sustainable systems, focusing on technological innovation and social justice for an equitable transition. The transport sector presents unique challenges, with electric transport modes fulfilling a significant portion of energy needs [11, 17, 9].

2.7 Interrelation and Relevance to EU Policy

The interrelation of open-source technology, justice transition, and sustainable energy shapes the EU's policy framework, emphasizing transparency, equity, and sustainability. Open-source technology fosters innovation and inclusivity, aligning with the EU's commitment to collaborative governance [4]. Integrating machine learning accelerates energy advancements, supporting EU policy goals [42].

Justice transition balances socio-economic impacts, ensuring vulnerable populations are not disproportionately affected. Effective policy mixes activate drivers and mitigate barriers, fostering an inclusive transition [21]. Sustainable energy systems underscore the EU's commitment to innovation and responsibility, with integrated models informing policy [43].

The EU's hydrogen strategies highlight global momentum towards hydrogen in sustainable systems. Policy support for hydrogen infrastructure ensures sustainability and resilience. Integrating Industry 4.0 technologies transforms supply chains, enhancing transparency and efficiency [42]. The integration of Direct Air Capture (DAC) and Green Hydrogen (GH) technologies optimizes energy use, relevant to EU policy on sustainable energy [21].

In recent years, the transition to sustainable energy systems has been significantly influenced by advancements in open-source technology. This paper explores the multifaceted role of these technologies in facilitating energy transition, emphasizing their innovative potential. Figure 2 illustrates the hierarchical structure of open-source technology applications in energy transition, highlighting

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key elements such as innovative technologies, artificial intelligence (AI) and machine learning (ML) applications, collaborative and decentralized solutions, as well as their integration with renewable energy sources and smart grids. By examining this structure, we can better understand how these components interact and contribute to a more sustainable energy future.

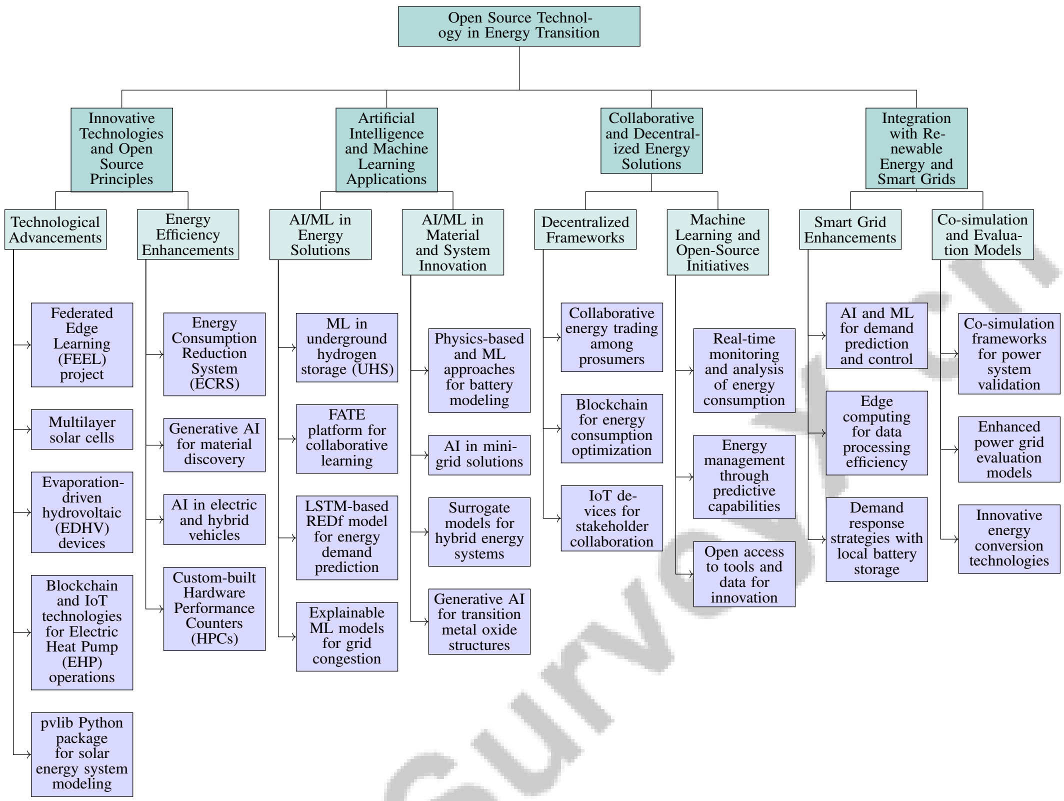

Figure 2: This figure illustrates the hierarchical structure of open-source technology applications in energy transition, highlighting innovative technologies, AI and ML applications, collaborative and decentralized solutions, and integration with renewable energy and smart grids.

3 Open Source Technology in Energy Transition

3.1 Innovative Technologies and Open Source Principles

Open-source principles have catalyzed significant technological advancements in the energy sector by promoting transparency, collaboration, and rapid innovation. The Federated Edge Learning (FEEL) project exemplifies this by enhancing prediction accuracy and privacy for prosumers through a decentralized approach, empowering energy consumers and producers [44]. Similarly, multilayer solar cells that optimize bandgap combinations demonstrate the potential of open-source methodologies to surpass the efficiency limits of traditional single-layer technologies [45].

To illustrate these advancements, Figure 3 highlights the integration of open-source principles and innovative technologies in the energy sector, showcasing key applications such as Federated Edge Learning, multilayer solar cells, and the convergence of blockchain and IoT technologies. This figure also emphasizes the role of artificial intelligence in enhancing energy systems and vehicle performance.

Innovations such as evaporation-driven hydrovoltaic (EDHV) devices, which merge thermodiffusion and photovoltaic effects, significantly enhance power output and efficiency [46]. Open-source initiatives have also advanced blockchain and IoT technologies, as exemplified by the public sector's Proof of Concept (PoC) for optimizing Electric Heat Pump (EHP) operations based on low-carbon energy availability [47]. The pvlib Python package further exemplifies open-source innovation, providing a structured API for solar energy system modeling [48].

The Energy Consumption Reduction System (ECRS) analyzes user consumption patterns to offer personalized energy-saving recommendations, showcasing the role of open-source platforms in enhancing energy efficiency [49]. Moreover, the integration of generative AI with dataset triage accelerates material discovery, reflecting the collaborative nature of open-source initiatives [24].

AI applications in electric and hybrid vehicles, including predictive maintenance and energy optimization, underscore the impact of open-source principles on vehicle performance and sustainability [2]. Custom-built Hardware Performance Counters (HPCs) enhance security in energy systems by detecting firmware modifications [25]. Collectively, these examples illustrate the transformative influence of open-source principles in promoting sustainable solutions and collaborative development within the energy sector [4, 43, 5].

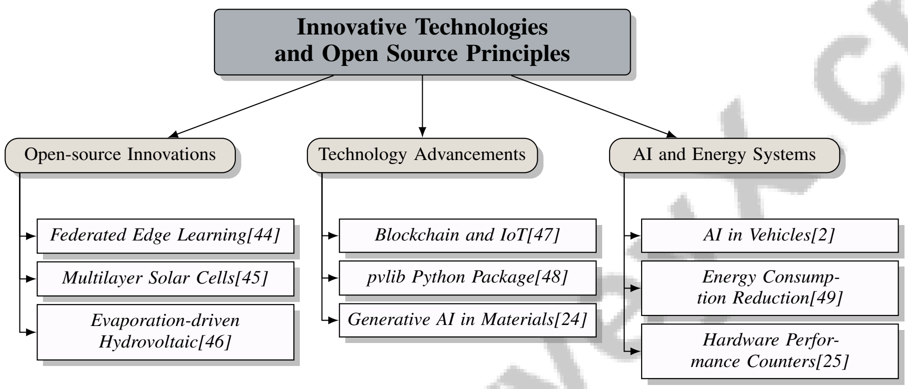

Figure 3: This figure illustrates the integration of open-source principles and innovative technologies in the energy sector, highlighting key advancements and applications such as Federated Edge Learning, multilayer solar cells, and blockchain-IoT convergence. It also showcases AI's role in enhancing energy systems and vehicle performance.

3.2 Artificial Intelligence and Machine Learning Applications

Artificial Intelligence (AI) and Machine Learning (ML) are pivotal in advancing open-source energy solutions, enhancing efficiency, scalability, and innovation. ML integration in underground hydrogen storage (UHS) modeling optimizes resource allocation while reducing computational costs [36]. The FATE platform exemplifies collaborative learning, allowing multiple parties to train ML models on their data without sharing sensitive information, thereby enhancing privacy and security [50].

AI models, such as the LSTM-based REDf model, show promise in accurately predicting short-term energy demand, while explainable ML models for redispatch and countertrade volumes emphasize transparency in grid congestion dynamics [51, 52]. Combining physics-based and ML approaches offers a robust framework for battery modeling, addressing the limitations of data-driven predictions [34].

AI's application in mini-grid solutions highlights diverse methodologies for optimizing energy generation and distribution [53]. Techniques like Kriging and Artificial Neural Networks (ANN) are vital for developing effective surrogate models for hybrid energy systems, contributing to enhanced performance and sustainability [54]. Generative AI methodologies, such as CDVAE and LLM, facilitate the discovery of transition metal oxide structures for multivalent-ion batteries, showcasing AI's potential in material innovation [24].

In the automotive sector, AI improves manufacturing efficiency and cybersecurity in electric and hybrid vehicles, underscoring its role in sustainable transportation [2]. However, the escalating computational demands of AI and ML raise concerns regarding energy consumption and carbon emissions, necessitating strategies to balance these advancements with environmental sustainability [13]. These applications collectively illustrate AI and ML's transformative potential in open-source energy solutions, fostering innovation and collaboration across various domains [55, 56, 14, 5].

3.3 Collaborative and Decentralized Energy Solutions

Open-source technologies significantly enhance collaborative and decentralized energy solutions, promoting inclusivity and efficiency in energy markets. A notable instance is the decentralized framework for collaborative energy trading among prosumers, which fosters market inclusivity by enabling community-level energy exchanges [44]. Open-source platforms are fundamental for developing decentralized solutions, providing infrastructure for real-time data sharing and decision-making, facilitating the integration of various sustainable energy sources.

Blockchain technology's transparency and immutability optimize energy consumption, support peer-to-peer trading, and enhance microgrid control, contributing to a resilient energy ecosystem [4, 47, 57]. The integration of IoT devices further enhances collaboration among stakeholders, enabling seamless communication and coordination across energy systems.

Blockchain enhances transparency and security in decentralized transactions through distributed data storage, encryption, and smart contracts, addressing challenges within the Energy Internet landscape [47, 38, 37, 4, 10]. This technology promotes trust and supports automated transactions, reducing administrative overheads.

Machine learning algorithms augment decentralized solutions by enabling real-time monitoring and analysis of energy consumption, optimizing distribution, and facilitating dynamic adjustments to meet demand fluctuations [4, 56, 14, 5]. These algorithms enhance energy management through predictive capabilities, ensuring stability and reliability.

The collaborative nature of open-source initiatives fosters innovation and experimentation in decentralized energy solutions, addressing the complexities of the Energy Internet [4, 58, 5]. By providing open access to tools and data, these initiatives empower developers to explore new energy management approaches, fostering continuous improvement essential for tackling the evolving challenges of the energy sector.

3.4 Integration with Renewable Energy and Smart Grids

Integrating open-source technology with renewable energy and smart grids is crucial for advancing sustainable energy management. This integration enhances energy systems' efficiency, reliability, and scalability through transparency, collaboration, and innovation. AI and ML techniques play a pivotal role by optimizing management, predicting demand, and automating control processes within smart grids [52].

Edge computing technologies improve smart grid capabilities by enhancing data processing efficiency and reducing latency [57], supporting real-time decision-making and aligning energy supply with consumer demands. Demand response strategies integrated with local battery storage exemplify how open-source technology can bolster renewable energy systems' stability and efficiency [59].

Co-simulation frameworks that integrate real-world components with simulation models validate power system control applications [60]. These frameworks optimize smart grid operations, ensuring robustness against operational challenges. Enhanced power grid evaluation models simulate interactions between electrical infrastructures and ICT components, providing insights into the impacts of failures and attacks [1].

Innovative energy conversion technologies, such as evaporation-driven hydrovoltaic (EDHV) devices, illustrate the potential for integrating ambient heat and solar energy into electrical power, enhancing renewable energy efficiency [46]. AI-driven approaches, including machine learning and neural networks, optimize power generation and distribution, facilitating seamless renewable energy integration [56].

The Resilience-Oriented Operation of Micro-Grids (ROM-MG) method enhances distribution networks' resiliency and efficiency through network reconfiguration strategies [61]. Additionally, methodologies identifying the IBR penetration threshold utilize dynamic simulations to ensure reliability during the energy transition [62].

4 Justice Transition and Social Equity

4.1 Social Equity in Energy Access

Ensuring social equity in energy access is essential for a just transition, particularly for underserved and marginalized communities. As illustrated in Figure 4, the hierarchical structure of social equity in energy access categorizes key aspects into technological innovations, economic factors, and educational and privacy solutions, each contributing to equitable energy distribution and access. Technological innovations such as UAVs for energy transfer improve distribution fairness, especially for low-power devices [63]. Peer-to-peer energy cooperation frameworks enable buildings to collaboratively reduce costs, enhancing access and promoting equity [26]. The eGLB method ensures equitable distribution of environmental costs associated with AI technologies, aligning with social-ecological justice goals and benefiting all societal groups [64]. This approach is crucial for addressing climate change while promoting equity, particularly in marginalized communities [65]. AI-driven mini-grid solutions further advance energy access in rural areas, underscoring technology's role in enhancing distribution equity [53].

Economic factors, such as disposable income and sustainable technologies like e-bikes, significantly influence social equity in energy access. The rise in e-bike sales highlights economic accessibility's role in fostering equitable energy solutions [66]. The EnergAIze initiative demonstrates how prosumers can manage consumption effectively, reducing peak demand and emissions, thereby enhancing equity [28]. In Sub-Saharan Africa, economic growth and clean energy access are pivotal for human development, emphasizing equitable energy access's importance in promoting social equity [67]. Democratizing optimization solutions through approaches like EC tailors energy management to individual preferences, enhancing accessibility [68].

Technology can democratize energy education, as shown by using smartphone sensors to measure solar irradiance, empowering resource-limited communities to engage with complex energy systems [69]. The w-PPSM framework ensures privacy at low costs while facilitating high-fidelity data sharing, crucial for promoting social equity in energy access and distribution [22].

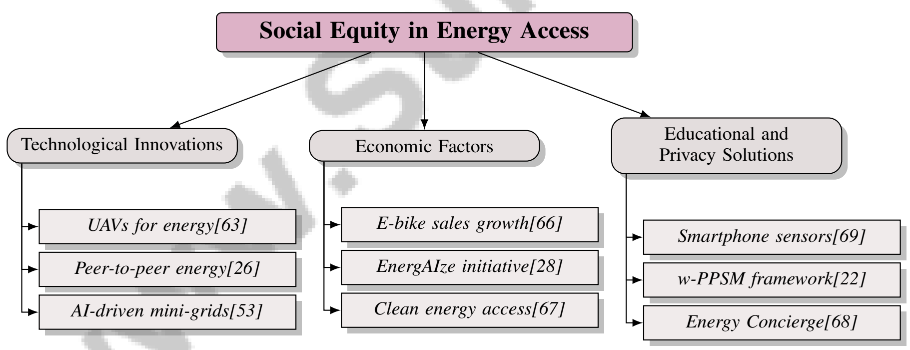

Figure 4: This figure illustrates the hierarchical structure of social equity in energy access, categorizing key aspects into technological innovations, economic factors, and educational and privacy solutions, each contributing to equitable energy distribution and access.

4.2 Policy and Governance Frameworks

Policies and governance frameworks are vital for a just transition, ensuring equitable, inclusive, and sustainable energy systems. Integrating blockchain technology into supply chains enhances transparency and accountability but presents challenges in justifying investment [10]. Robust policy frameworks are needed to encourage innovative technology adoption while addressing economic and regulatory constraints [37]. High-resolution synthetic residential energy benchmarks inform policy and technology advancements, promoting fairness and inclusivity in energy access [70]. These benchmarks enable comparisons of consumption patterns, guiding policy formulation for equitable distribution.

Acknowledging high-emitting countries' historical responsibilities in climate change is vital within policy frameworks. These nations must assist less developed countries in their energy transitions to

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ensure fair and inclusive climate action [65]. This perspective aligns with justice transition goals, prioritizing long-term equity over short-term economic gains. Community-driven models, as explored in studies on Free Software, demonstrate collaborative governance approaches' effectiveness [29]. These models emphasize openness and collaboration, essential for fostering innovation and inclusivity in energy systems. By leveraging community-driven strategies, governance frameworks can promote a more participatory and equitable energy transition.

4.3 Technological Innovations and Equity

Technological innovations are crucial for advancing equity in the energy transition by enhancing accessibility, affordability, and efficiency across diverse communities. Integrating High-Performance Computing (HPC) in energy management systems optimizes resources, reduces emissions, and promotes equity by ensuring efficient and environmentally responsible systems [13]. Detecting firmware attacks with Hardware Performance Counters (HPCs) enhances energy access reliability and security, ensuring stable systems for all users [25].

Innovations in building energy management, such as identifying factors affecting consumption and costs, provide actionable insights promoting equity by enabling efficient use and cost savings in residential and commercial settings [71]. This ensures accessible and affordable energy solutions, contributing to a more equitable transition. Foundation models for time series forecasting simplify the process and improve accuracy without extensive retraining [16]. This capability is crucial for optimizing distribution and consumption patterns, particularly in decentralized systems where accurate forecasting ensures equitable access.

Social interactions, like gaining new followers, significantly influence developers' contributions, highlighting the importance of fostering inclusive and collaborative environments in open-source communities [43]. Encouraging diverse participation and contributions can drive innovation and equity in energy solutions, ensuring technological benefits are widely shared across sectors and communities.

5 Common Batteries Model and Sustainable Energy

5.1 Technological Innovations in Battery Systems

Advancements in battery systems are pivotal for the common batteries model, enhancing energy storage and distribution in sustainable systems. MambaLithium exemplifies this by improving estimation accuracy and computational robustness in battery management systems [32]. Surrogate modeling, including digital twins and AI, facilitates simulation and optimization, making battery systems adaptable to evolving demands [54]. Model predictive control (MPC) in electric aviation networks highlights reduced grid dependency and improved energy management [72]. Multilayer solar cells have achieved significant efficiency gains, enhancing energy capture and storage, thereby supporting the common batteries model [45]. Battery energy storage systems mitigate reduced system inertia from high inverter-based resource penetration, ensuring reliable renewable integration [62]. Moreover, efficient cooperative anycasting in AMI mesh networks optimizes resource utilization and data transport, enhancing smart grid operations [23].

Figure 5 illustrates the key technological innovations in battery systems, categorizing advancements into battery management, energy optimization, and smart grid operations. Each category highlights specific methodologies and technologies that contribute to the improvement of energy storage, distribution, and grid reliability. This visual representation complements the discussion by providing a structured overview of how these innovations interrelate and support the overarching goals of modern energy systems.

5.2 Case Studies and Implementation Examples

The EU's implementation of the common batteries model is exemplified by innovative projects across member states. Germany's Energiewende initiative utilizes battery energy storage systems for frequency regulation and peak shaving, ensuring reliable renewable integration [62]. In the Netherlands, smart grid projects leverage real-time analytics and predictive modeling for effective energy management, reducing fossil fuel reliance [72]. Spain maximizes solar PV utilization through

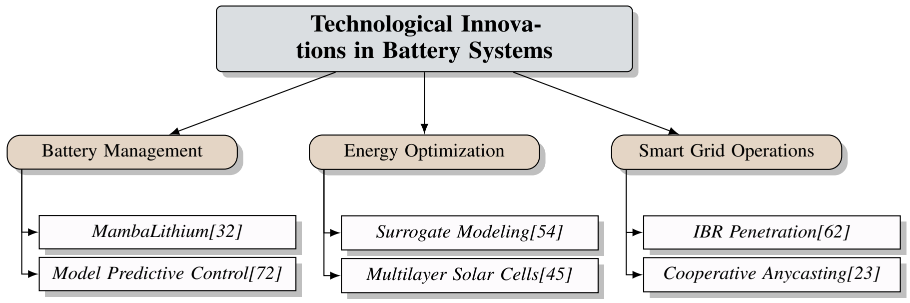

Figure 5: This figure illustrates the key technological innovations in battery systems, categorizing advancements into battery management, energy optimization, and smart grid operations. Each category highlights specific methodologies and technologies that contribute to the improvement of energy storage, distribution, and grid reliability.

battery systems, smoothing power intermittency and supporting carbon neutrality goals [45]. Italy's AMI mesh networks employ cooperative anycasting to optimize data transport, crucial for efficient energy storage and distribution in high renewable regions [23]. These case studies underscore the EU's commitment to sustainable energy systems, achieving cost savings and synergies through diverse storage solutions [73, 4, 5, 3].

5.3 Challenges in Implementation

Implementing the common batteries model in sustainable systems faces challenges that impact effectiveness and scalability. Parameter identifiability in electrochemical models limits extrapolation, necessitating comprehensive datasets and advanced modeling techniques [34]. Oversimplified battery models lack insights into internal processes, highlighting the need for detailed approaches reflecting operational complexities [74]. Scalability issues with all-solid-state batteries (ASSBs) arise from overlooked manufacturing and recycling strategies [31]. Assumptions of infinite reservoirs in storage methods necessitate realistic models for resource optimization [75]. Scheduling accuracy can be compromised by unaccounted losses in storage capacity and transmission, requiring mitigation strategies [33]. Decentralized trading systems face data security threats, emphasizing robust security measures [44]. Uniform uncertainty assumptions across storage technologies complicate evaluation, necessitating nuanced models [3]. Selecting optimal materials for inverse photoelectrochemical cells (IPEC) is critical for efficiency, warranting ongoing research [76]. Communication losses in peer-to-peer frameworks complicate negotiations, necessitating improved infrastructure [26]. Scalability and durability of materials in energy applications remain challenges, requiring innovation for widespread implementation [41]. Balancing computational demands with sustainable practices presents further challenges in energy-efficient computing [13].

6 Open Source Supply Chain Management

6.1 Opportunities for Collaboration and Efficiency

The integration of open-source frameworks and artificial intelligence (AI) significantly enhances collaboration and efficiency in sustainable energy supply chains. Open-source models like UPNet drive catalyst discovery, boosting supply chain efficiency [77], while tools such as PyBaMM facilitate battery modeling collaboration, allowing researchers to customize models for specific needs [78]. Blockchain technology further enhances collaboration by providing transparent and traceable transactions, which increases accountability and efficiency in open-source supply chains [10]. Platforms like GitHub support this transparency by offering complete source codes for supply chain management innovation [79].

Integrating flexibility assets, including batteries and electric vehicles, into home energy management systems exemplifies how open-source frameworks enhance system efficiency and collaboration [80]. AI optimizes supply chain operations through predictive analytics and adaptive decision-making, improving operational efficiency and stakeholder collaboration by offering actionable insights into supply chain dynamics [5]. The MambaLithium model showcases AI's capability to model complex nonlinear battery data patterns, aiding supply chain optimization while ensuring computational efficiency [32].

6.2 Blockchain and Supply Chain Innovations

Blockchain technology revolutionizes supply chain management by enhancing transparency and efficiency in sustainable energy systems. Its decentralized ledger provides transparent, immutable transaction records, minimizing fraud risk and fostering stakeholder trust [37]. This transparency is crucial for collaboration and accountability, enabling precise tracking of products and materials across the supply chain. Figure 6 illustrates the key innovations in blockchain technology for supply chain management, highlighting the benefits, integration with other technologies, and alignment with sustainability goals.

Blockchain's effectiveness is amplified through its integration with the Internet of Things (IoT) and AI. IoT devices enable real-time data collection and sharing via RFID tags and sensors, which AI algorithms analyze to optimize operations and predict disruptions, thus enhancing supply chain performance [39, 37, 81, 10]. These technologies together improve supply chain visibility and responsiveness, allowing for proactive management and decision-making.

Additionally, blockchain supports smart contracts that automate transactions based on predefined conditions, streamlining operations and reducing administrative burdens. This automation is particularly advantageous in complex supply chains, where AI and IoT enhance operational efficiency and minimize human error [39, 37]. The integration of blockchain and these innovations supports supply chain sustainability by continuously monitoring and verifying environmental and social compliance. This capability enhances transparency and accountability, facilitating IoT applications that improve resource optimization and stakeholder engagement. Organizations adopting these technologies can align with triple bottom line principles—addressing social, economic, and environmental factors—thus advancing sustainability goals and regulatory compliance [37, 38, 10]. By ensuring transparent and accountable supply chain activities, blockchain empowers organizations to meet sustainability standards and uphold responsible practices.

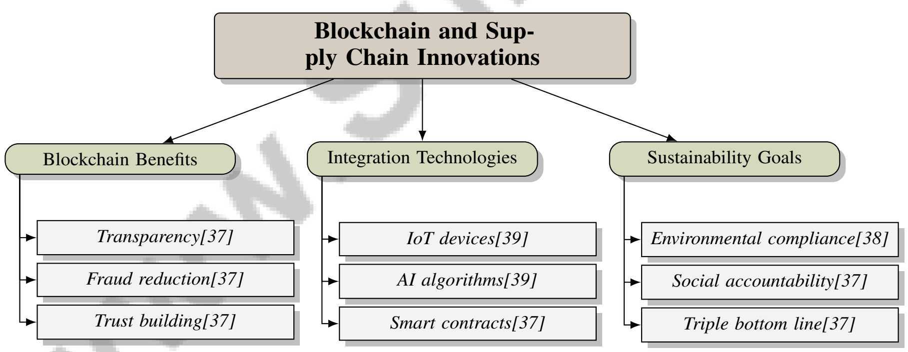

Figure 6: This figure illustrates the key innovations in blockchain technology for supply chain management, highlighting the benefits, integration with other technologies, and alignment with sustainability goals.

7 European Union Policy and Sustainable Energy

7.1 Policy Effectiveness and Future Directions

The integration of technological innovations within European Union (EU) policies significantly enhances their effectiveness in achieving sustainability goals. Table 1 provides a detailed overview of representative benchmarks used in energy systems research, illustrating their relevance to the integration of technological innovations within EU policies for sustainability. The IBR penetration threshold identification methodology exemplifies the EU's strategic approach to renewable energy integration, aiding utilities in planning for increased renewable sources [62]. This methodology underscores the EU's commitment to embedding renewable energy within existing power systems.

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Benchmark	Size	Domain	Task Format	Metric
Predict+Optimize[82]	1,000,000	Energy Scheduling	Scheduling	MASE, Energy Cost
GloSoFarID[83]	13,703	Solar Energy	Segmentation	IoU, F-score
FlexiGen[84]	1,000	Energy Flexibility	Dataset Generation	Energy Flexibility, Charging Efficiency
BH-IoT[81]	22,033	Building Energy Management	Multivariate Forecasting	SMAPE, R2
DAC-GH[85]	1,000	Energy Systems	Economic Analysis	LCOH, LCOD
STLF-FM[16]	300	Household Electricity	Short-term Load Forecasting	MAE households, MSE households

Table 1: This table presents a comprehensive overview of representative benchmarks utilized in the context of energy-related research. It details the benchmarks by their size, domain, task format, and evaluation metrics, highlighting their diversity and application in various energy systems and policies.

Sustainable transportation policies are bolstered by e-bike sales forecasting studies, advancing eco-friendly transportation initiatives [66]. Aligning transportation with sustainability objectives promotes low-carbon technology adoption and reduces greenhouse gas emissions. Furthermore, refining policy frameworks to support energy infrastructure and technological innovation is vital for sustainable development [67]. This includes incentivizing adaptive ecological discharge methods in hydropower, contributing significantly to sustainability goals [15].

Blockchain technology enhances supply chain transparency and cost efficiency, aligning with EU policies promoting efficient energy supply chains [37]. Sustainable computing practices, especially High-Performance Computing (HPC), are crucial for advancing sustainable energy technologies [13]. Promoting sustainable design in AI and computing aligns technological progress with EU sustainability goals.

Future research should refine justice-based frameworks, improve emissions and equity data collection, and develop policies prioritizing disadvantaged groups. Exploring hybrid modeling architectures and enhancing experimental designs can augment the EU's capacity to address complex energy challenges. By addressing interconnected sustainability aspects, EU policies can better meet sustainability objectives, facilitating efficient and equitable energy transitions. This alignment is crucial for environmental challenges, public health, job creation, and broader energy access. Developing comprehensive indicators for sustainable energy progress will enable effective collaboration among policymakers, businesses, and communities, ensuring an inclusive transition to renewable energy [6, 17].

7.2 Policy and Economic Considerations

Economic considerations are central to shaping EU policy implementation in sustainable energy transitions. Integrating advanced technologies like AI and blockchain requires substantial investment, posing financial challenges for public and private sectors. The cost-effectiveness of these technologies influences policy decisions, necessitating economic evaluations of blockchain investments in supply chain management [10]. Policymakers must assess economic benefits and return on investment to advance sustainable energy objectives without imposing financial burdens.

The EU prioritizes renewable energy sources, such as solar and wind, to reduce fossil fuel dependency and greenhouse gas emissions. However, high initial capital costs for renewable infrastructure can hinder policy implementation. Economic incentives, including subsidies and tax breaks, are crucial for encouraging renewable project investment and grid integration [13]. These incentives offset high upfront costs, making renewable solutions attractive to investors and consumers.

The economic viability of energy storage technologies, particularly batteries, is critical in policy formulation. Developing cost-effective, scalable energy storage solutions ensures reliability and stability in renewable systems. Policies supporting battery technology research and robust supply chains for critical materials are necessary to enhance economic feasibility [32]. Innovation and cost reduction can accelerate energy storage adoption, strengthening the EU's sustainable energy infrastructure.

Assessing energy policies' economic impact on various sectors and communities ensures equitable outcomes. Sustainable energy transitions affect employment and economic growth differently across regions, requiring targeted policies addressing unique needs. Regions reliant on fossil fuel industries may need workforce retraining and economic diversification support to mitigate transition effects [67].

7.3 Technological Advancements and Policy Support

Technological advancements in sustainable energy are crucial for achieving EU sustainability objectives, with policy playing a vital facilitative role. AI-driven solutions in electric vehicle manufacturing illustrate AI's potential in sustainable energy systems, enhancing policy effectiveness in energy transitions [2]. Policies promoting AI integration in manufacturing can significantly improve electric vehicle sustainability and efficiency, aligning with EU carbon emission reduction commitments.

The w-PPSM framework highlights policy support for technological advancements in sustainable energy through privacy-preserving mechanisms, enabling coordinated heat and electricity markets while safeguarding consumer data [22]. This underscores the importance of policy support for technologies enhancing efficiency and privacy in energy systems.

Model Predictive Control (MPC) schemes in energy management showcase policy support for advanced control strategies in sustainable energy systems [72]. The adaptive cooperative anycasting method addresses smart grid communication issues, demonstrating policy support for technological advancements enhancing energy system reliability and efficiency [23].

Blockchain technology's potential to enhance the Energy Internet by addressing trust issues and enabling decentralized energy trading is another area where policy support is crucial [4]. Fostering blockchain adoption can enhance transparency and security in energy transactions, contributing to a resilient, efficient energy infrastructure.

Policy support for technological advancements securing microgrid systems against firmware attacks is essential for sustainable energy transitions [25]. Prioritizing cybersecurity measures ensures energy systems' integrity and reliability, critical for maintaining consumer trust and promoting sustainable energy solutions.

Future research in material discovery will focus on exploring open-source models and enhancing LLM quantization to improve stable materials generation [24]. Policy support for such initiatives can accelerate advanced materials development, vital for improving energy systems' efficiency and sustainability.

7.4 Market Dynamics and Regulatory Frameworks

Market dynamics and regulatory frameworks are pivotal in shaping the sustainable energy sector, influencing renewable energy technology deployment and operational efficiency. In the EU, concentrated solar power (CSP) analysis identifies key drivers like supportive policies and technological advancements enhancing dispatchability, crucial for overcoming barriers like administrative hurdles and grid connectivity challenges. AI integration in energy systems optimizes renewable technologies, necessitating a comprehensive policy mix addressing economic and technological energy transition dimensions [19, 8, 5]. Integrating renewables into markets requires understanding market mechanisms and regulatory policies fostering innovation, competition, and sustainability. The EU's carbon neutrality commitment by 2050 emphasizes regulatory frameworks supporting a low-carbon economy transition, highlighting policies encouraging renewable energy infrastructure and technology investment.

Market-based instruments, such as carbon pricing and emissions trading systems, influence energy sector dynamics. These mechanisms create economic incentives for reducing greenhouse gas emissions, encouraging cleaner technology investment and distributed energy resources (DERs) integration like solar and wind power. As renewables become more prevalent, they contribute to electricity market price volatility, posing financial risks to participants. To mitigate these risks and enhance market efficiency, innovative solutions like insurance markets and local energy trading systems enable prosumer energy trading, promoting a sustainable energy future [86, 87, 88]. These instruments internalize carbon emissions' environmental costs, promoting cleaner energy production methods. Market-based approaches' effectiveness hinges on robust regulatory frameworks ensuring transparency, accountability, and fairness.

AI-generated, for reference only.

Regulatory frameworks effectively integrate DERs into energy markets, establishing conditions for small prosumers with solar panels and energy storage to participate actively. Promoting market efficiency and grid flexibility, these frameworks facilitate mechanisms allowing multiple DER aggregators to bid on behalf of asset owners, shaping wholesale electricity prices and improving market stability. Policies addressing deployment barriers ensure technologies like CSP and energy storage contribute significantly to a sustainable energy future [19, 8, 3, 4, 87]. DER deployment requires regulatory support addressing technical, economic, and operational challenges. Policies promoting grid modernization and smart grid technologies accommodate increased DER penetration, ensuring grid stability and optimizing energy flow.

The regulatory environment must evolve to address modern energy markets' complexities, increasingly influenced by digitalization and advanced technologies like blockchain and AI. These technologies enhance distributed sustainable energy system management by improving transparency and efficiency through decentralized data storage and smart contracts, optimizing energy infrastructure and decision-making processes. Regulators must adapt frameworks to accommodate these innovations, ensuring they support sustainable practices while addressing emerging security and operational efficiency challenges [2, 4, 10, 5]. These technologies offer opportunities for enhancing market efficiency, transparency, and security but present new regulatory challenges related to data privacy, cybersecurity, and market manipulation. Regulatory frameworks must balance innovation with consumer rights and market integrity protection.

The EU's sustainable energy regulatory approach focuses on fostering regional cooperation among member states and harmonizing energy policies, creating a cohesive framework supporting robust sustainable energy initiative indicators. This collaborative effort addresses interdependencies between energy production, environmental sustainability, and technological advancements, ensuring policies are effective and adaptable to future challenges [89, 6, 9]. This approach facilitates developing an integrated energy market leveraging countries' strengths while addressing common challenges. By fostering cross-border collaboration and aligning regulatory standards, the EU aims to create a resilient, competitive energy market supporting a sustainable energy future transition.

8 Conclusion

8.1 Future Directions and Research Opportunities

Advancing sustainable energy and open-source technology requires a focus on the adaptability of Free Software practices to address modern challenges, thereby enhancing innovation and collaboration. The development of sophisticated AI models for optimizing electric vehicles presents opportunities to improve energy efficiency, with a particular emphasis on ethical data management. Enhancing the reliability of large language models in problem formulation is crucial for effective energy management and fostering sustainable energy adoption.

The integration of new technologies to boost transport efficiency and the study of decentralized energy systems are key areas for future research, particularly concerning urban air quality and energy optimization. Crafting adaptive policies for renewable energy transitions and investigating technologies that enhance the resilience of energy systems are essential for supporting sustainable energy frameworks.

Standardizing regulatory frameworks and innovatively applying blockchain technology across energy sectors are necessary to tackle energy consumption challenges and enhance transparency and efficiency. Expanding datasets, identifying additional features, and refining algorithms are vital for improving prediction accuracy and applicability across various building types, advancing energy efficiency and management strategies.

Research should also focus on sustainable computing strategies that utilize advancements in hardware efficiency, energy management, and algorithmic sustainability, contributing to an environmentally responsible computing landscape. Exploring natural experiments to validate findings and examining other factors influencing contributions can inform policy development in open-source software engagement strategies.

Addressing these research opportunities can drive the field towards more sustainable, equitable, and innovative energy solutions, ultimately contributing to a resilient and environmentally responsible energy future.

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