Driving Sustainability in Telco and Data Centers: A Technical Evaluation on Kepler’s Potential

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Abstract **-** Kepler, a Kubernetes-based Efficient Power Level Exporter and CNCF sandbox project, transforms energy monitoring and optimization for Telecommunications (Telco) and data center operations. Leveraging cutting-edge technologies like eBPF (extended Berkeley Packet Filter) and machine learning, Kepler offers granular insights into pod-level energy consumption, facilitating dynamic resource allocation and global sustainability compliance [1]. This paper evaluates Kepler’s technical framework, examining its role in advancing sustainability through 5G workload profiling, ICT scalability, edge computing, and beyond. Kepler has the potential to serve as a transformative solution for achieving net-zero carbon goals and driving future-ready digital ecosystems.

1. Introduction

Telco and data centers form the backbone of modern digital infrastructure. Driving global communication networks, cloud services, and enterprise operations. However, the rapid expansion of these industries brings heightened environmental challenges, particularly in energy consumption and carbon emissions. Amid increasing scrutiny, these industries face rising pressure to adopt sustainability-focused solutions that balance performance with environmental responsibility. Global initiatives like the European Union’s Green Deal and compliance standards such as Scope 2 emissions and the Greenhouse Gas Protocol mandate the development of precise energy monitoring and optimization tools to meet long-term planning and sustainability goals [2][3]. By providing granular, real-time energy insights and resource optimization capabilities, Kepler empowers organizations to align operations with sustainability KPIs (Key Performance Indicators) while maintaining operational efficiency [2][3]. This paper explores Kepler’s capabilities and its applications in 5G workload profiling and edge computing, focusing on its potential to enhance energy optimization and scalability in cloud-native environments. Furthermore, it explores Kepler's potential in enabling industries to adapt to evolving environmental standards while advancing toward a sustainable ICT ecosystem [4].

2. Kepler – A Framework for Addressing Sustainability Challenges

While cloud-native environments have revolutionized application deployment, their growing complexity poses significant sustainability challenges. Kepler emerges as a robust framework designed to address the energy inefficiencies of cloud-native

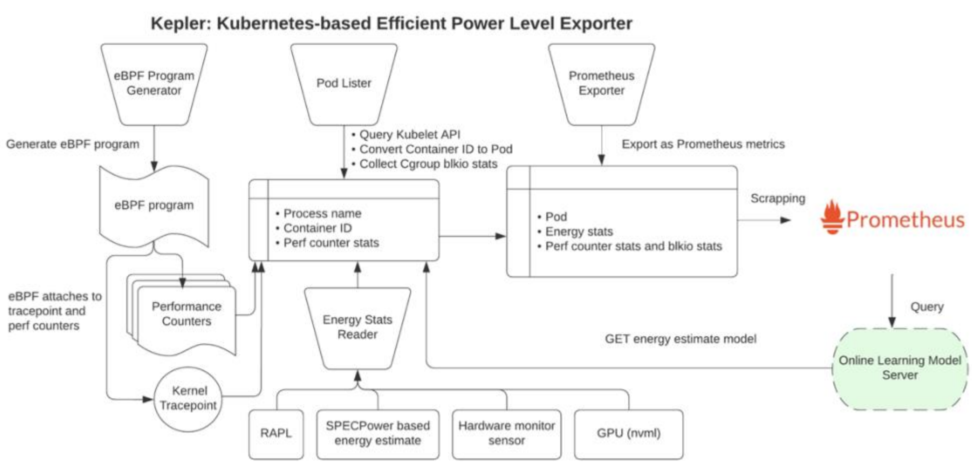

Fig.1: Kepler Architecture [5]

environments [1]. Kepler's innovative use of cutting-edge technologies supports sustainable practices by employing a multi-layered technical architecture to address energy inefficiencies in cloud-native environments [1][5].

2.1 Technical Framework

Kepler collects performance data from kernel trace points and hardware sensors using APIs such as Intel's RAPL (Running Average Power Limit), NVIDIA's NVML (NVIDIA Management Library), and ACPI (Advanced Configuration and Power Interface). These hardware-level power monitoring technologies complement eBPF-driven insights, enabling detailed and accurate power metrics at the pod or container levels [3]. The collected data is processed by the Energy Stats Reader and further refined by an online learning model server. The model server dynamically updates energy estimation models, enabling accurate power profiling even in heterogeneous environments like virtual machines (VMs). This architecture allows Kepler to provide real-time, pod-level energy consumption metrics, facilitating actionable insights for optimization and regulatory compliance in Kubernetes-based ecosystems [3][5]. Figure 1 provides a visual representation of Kepler's modular architecture, emphasizing its use of eBPF for kernel-level instrumentation, the integration of Prometheus for observability, and the customizable deployment options available via Kepler's GitHub repository [5].

2.1.1 eBPF Technology for Precise Energy Monitoring

At the heart of Kepler lies eBPF, a Linux kernel technology enabling lightweight and real-time system instrumentation. The framework leverages eBPF to collect power consumption data at the pod-level within Kubernetes clusters. This functionality facilitates efficient, low-overhead monitoring, enabling energy metrics to be collected and analyzed in real-time [1][3]. eBPF is particularly suited for this use case because it operates directly within the Linux kernel, minimizing performance overhead while providing precise, event-driven insights at the process level. This detailed view empowers enterprises and individuals to measure, predict, and optimize energy usage dynamically, reducing carbon footprints without significant overhead—a critical requirement in resource-intensive environments [3].

2.1.2 Predictive Power Profiling

The machine learning models in Kepler estimate power consumption trends based on collected metrics. Linear regression is used for simplicity and efficiency, allowing Kepler to establish baseline correlations between resource utilization and energy usage [1]. This approach provides a foundation for exploring more complex models as workload diversity increases [3]. These models analyze correlations between system performance characteristics—such as CPU utilization, memory usage, and network activity—and their associated energy consumption [5]. By processing these relationships, Kepler provides actionable insights that help operators optimize workload placement and resource allocation while minimizing environmental impact [1][3].

2.1.3 Interoperability with Observability Ecosystems

Designed for seamless integration, Kepler supports open-source observability tools like Prometheus and visualization frameworks such as Grafana [5]. By integrating with Prometheus, Kepler exports energy metrics in a format that seamlessly integrates with existing monitoring pipelines, while Grafana's visualization capabilities enable operators to create intuitive dashboards for energy consumption analysis [5]. This interoperability allows operators to unify energy metrics with existing performance dashboards, enhancing decision-making and enabling tailored optimization strategies. Integration with cloud-native tools ensures that energy metrics can be analyzed alongside operational KPIs [1][2].
Kepler's robust architecture not only identifies energy inefficiencies but also enables organizations to adopt data-driven strategies for sustainable operations. By delivering actionable energy data and leveraging AI-driven insights, it plays a pivotal role in optimizing resource allocation and enhancing operational efficiency, particularly in distributed Telco and data center environments [3].

2.2 Application Scenario: Power Profiling for 5G Workloads and Data Centers

One of Kepler's most promising avenues lies in power profiling for 5G services and containerized workloads deployed as Cloud-Native Functions (CNFs) in data centers. These workloads often run on energy-intensive infrastructures, demanding practical tools to ensure compliance with environmental regulations [2]. Kepler addresses this need through the following process:

2.2.1 Energy Source Identification

By collecting data on energy usage, Kepler identifies whether workloads are powered by renewable or non-renewable energy sources [1]. By integrating with datasets obtained from regional energy grids, Kepler enables operators to track energy source attribution accurately, facilitating informed decisions to enhance sustainability and comply with environmental standards [3].

2.2.2 Dynamic Power Profiling

Kepler leverages its machine learning-based estimation models to analyze pod-level energy consumption metrics, enabling operators to profile

CNF cluster power usage, identify inefficiencies, and optimize resource allocation dynamically [1][3][5]. For instance, a telco operator might identify video streaming workloads consuming a disproportionate amount of energy and optimize them using Kepler's insights, reducing operational costs and emissions.

2.2.3 Sustainability Optimization

The framework provides actionable insights for energy source optimization, such as transitioning from non-renewable to regionally available renewable alternatives [3]. By aligning with Scope 2 emission regulations, Kepler supports telco operators in achieving compliance and reducing their carbon footprint [2]. For example, transitioning a single high-load CNF workload to renewable sources could reduce carbon emissions annually, aligning operations with industry sustainability benchmarks [2][3].

2.2.4 Green Energy Promotion

By forecasting energy consumption patterns, Kepler helps operators to plan resource allocation effectively [3]. This foresight supports prioritizing renewable energy adoption during peak load periods, contributing to reduced overall carbon footprints. Over time, this insight could help CSPs move beyond energy adoption strategies to broader initiatives, such as investments in renewable energy infrastructure [2].

2.2.5 Scalability for Multi-Cloud Environments

The architecture making Kepler ensures seamless scalability across hybrid cloud infrastructures, enabling organizations to maintain operational flexibility and sustainability in diverse operational landscapes [3][4]. A particularly valuable application of this scalability is in multi-cloud environments for disaster recovery, where workloads must dynamically shift between regions with varying energy regulations and resource availability. Additionally, Kepler extends its functionality by estimating dynamic power even in virtual machine (VM) environments where direct hardware metrics are unavailable [1][4]. Leveraging trained power models, the framework delivers robust energy insights, ensuring consistent operational flexibility across hybrid and multi-cloud scenarios [3].

2.3 Advancing Sustainability

Kepler exemplifies a transformative step toward integrating sustainability as a core metric in cloud-native infrastructure operations. By addressing energy inefficiencies with unprecedented granularity, the framework empowers organizations to meet their sustainability objectives without compromising operational demands [1][3]. This section evaluates Kepler's contributions, contrasts them with existing tools, and explores their limitations and potential future trajectories.

2.3.1 Strengths and Contributions

While energy monitoring solutions are not new, Kepler's approach stands out in depth and focus. Its detailed metrics for Kubernetes-specific workloads position it uniquely among tools like AWS CloudWatch and Google Cloud's Carbon Footprint Reporting, which lack its pod-level precision [3]. Tools like AWS CloudWatch and Azure Monitor offer sustainability insights as part of their product ecosystems but fail to match the granularity Kepler provides for Kubernetes-specific workloads [3][5]. These solutions are effective for broad cloud-wide metrics but are inherently tied to their respective infrastructures, limiting their applicability in heterogeneous or multi-cloud environments [4]. Kepler's capabilities provide significant benefits to industries where energy optimization directly impacts costs or ESG goals, such as:

- AI Research Labs: Reducing energy consumption for computationally intensive machine learning training [3].
- Telecom Operators: Optimizing energy use in 5G and edge networks to meet sustainability benchmarks [6].
- Green Energy Startups: Monitoring renewable energy integration within cloud-native infrastructures [4].

Consider a telecom operator deploying 5G edge nodes with Kepler as a hypothetical example. By analyzing power consumption across nodes, they identify underutilized clusters and implement workload redistribution, resulting in a 15% reduction in energy usage. Simultaneously, the operator aligns operations with Scope 2 emissions standards, contributing to ESG goals and reducing operational costs [2][6].

On the other hand, Prometheus and Grafana, integral to Kepler's architecture, excel in visualization and general observability. However, they lack the built-in AI-driven analytics that form Kepler's core strength [5]. Similarly, Google Cloud's Carbon Footprint Reporting aggregates emissions at a project level but does not offer real-time pod-level granularity or long-term data storage for nuanced historical analysis. This distinction positions Kepler as a uniquely valuable tool for Kubernetes environments, enabling precise forecasting, resource allocation, and actionable sustainability planning.

Kepler's platform-agnostic design extends its applicability beyond Kubernetes [3]. By supporting platforms like VMware Tanzu, AWS EKS, and standalone Linux servers, Kepler adapts seamlessly to diverse infrastructures [4]. Unlike tools tethered to specific cloud ecosystems, Kepler provides flexibility for hybrid and SaaS infrastructures, making it a compelling choice for data centers and Cloud Service

Providers (CSPs) operating in complex, distributed environments.

In addition, Kepler's dynamic adaptability across various hardware architectures—spanning CPU, GPU, and hybrid cloud workloads—enhances its versatility [1][3]. Its compatibility with both Kubernetes and non-Kubernetes environments extends its utility beyond its initial design scope, offering insights for diverse operational scenarios. For example, administrators can deploy Kepler's RPM on Linux servers to monitor energy usage of processes outside Kubernetes, highlighting its potential as a general-purpose sustainability tool [5]. Kepler's deployment in telco and data center environments has the potential to significantly enhance sustainability outcomes [1][2]. Enabling real-time monitoring and optimization supports operators in achieving ESG goals, an essential part of Kepler's value proposition. Its key features directly support sustainability objectives:

- Granular Energy Monitoring: Pod-level insights enable operational optimization while reducing waste [1].
- Renewable Energy Transition: The system provides region-specific recommendations for shifting workloads to renewable energy sources [1]. Its insights into energy consumption allow transparency, enabling operators to reduce reliance on non-renewable energy and transition to sustainable practices in a planned manner, balancing long-term sustainability with cost-effectiveness [6].
- Operational Efficiency: Kepler helps organizations reduce energy consumption by identifying inefficiencies while meeting Scope 2 emissions standards [2][6]. Kepler aligns with initiatives like the European Union's Green Deal and Carbon Disclosure Project (CDP), ensuring organizations meet international sustainability standards [2]. Additionally, Kepler optimizes workload allocation and resource utilization, reducing energy costs while maintaining performance standards [3].

Despite these strengths, scalability remains a significant challenge. While Kepler can monitor energy usage effectively in smaller-scale or isolated environments, its deployment in large, multi-cloud infrastructures poses logistical and computational hurdles [1]. High data volumes, varying workloads, and diverse infrastructure requirements may necessitate further optimizations to maintain performance without compromising its granularity or accuracy [2].

2.3.2 Limitations

While Kepler provides advanced capabilities, it is not without limitations. Addressing these challenges is critical for maximizing scalability, enhancing analytical precision, and expanding industry impact.

Predictive Modeling Enhancements: Kepler's reliance on linear regression models, while efficient, limits its ability to capture the complexity of non-linear workload behaviors [3]. Integrating more advanced machine learning techniques could enhance accuracy, especially for workloads with non-linear dynamics of heterogeneous energy usage patterns, especially those seen in AI training pipelines or fluctuating 5G network traffic [2][3][6]. Furthermore, Kepler's pre-trained power models face limitations in VM environments, including potential overestimations and challenges in dividing idle power accurately among shared resources [3]. Ongoing efforts to integrate hypervisors and develop dynamic power models aim to address these gaps, enhancing precision in diverse operational contexts [3]. Enhancements through deep learning or adaptive neural network techniques could provide a more nuanced analysis for such scenarios. Integrating advanced neural networks and adaptive learning algorithms would refine its predictive accuracy and support dynamic resource allocation. These improvements are particularly relevant for scaling energy-intensive applications, ensuring Kepler remains a reliable tool for diverse and evolving workloads [2][3].

Integration and Onboarding Challenges: Despite Kepler's platform-agnostic deployment, the integration process may present challenges for organizations unfamiliar with Kubernetes or Linux-based systems. Simplifying the onboarding process and expanding support for alternative orchestration platforms—including enhanced partnerships with major cloud providers such as AWS, Azure, and Google Cloud—could significantly improve accessibility and ease of adoption in hybrid or multi-cloud environments [3][4].

Enhanced integration with these platforms would not only facilitate broader scalability and market reach but also reduce deployment complexity for diverse teams. This streamlined approach would empower organizations to leverage Kepler's capabilities more effectively, fostering its adoption as a standard tool for sustainability-focused operations in cloud-native ecosystems [1][2].

Edge Computing and Renewable Energy Integration: Kepler's capabilities could be extended to support edge computing environments, where energy efficiency is critical due to limited resources [2][4]. By providing recommendations for integrating renewable energy sources like solar and wind, Kepler could significantly enhance sustainability planning for long-term energy solutions [1][2][6]. Use cases such as monitoring renewable energy microgrids or managing energy-efficient IoT networks in remote areas demonstrate the potential for Kepler to address resource-constrained and distributed environments effectively [4][6]. In addition to renewable energy planning, modular APIs enabling automated energy reallocation based on real-time grid demands could position Kepler as a critical tool for energy-efficient edge computing and Radio Access Networks (RAN) [2][3][6]. The adaptability of Kepler's framework extends to privacy-sensitive workloads in edge environments, where local data processing using edge AI techniques—such as federated learning to train models without transferring raw data—ensures both energy efficiency and data security [3].

2.4 Preparing for Future Industry Demands

As ICT ecosystems transition toward 6G and NextG networks, tools like Kepler will be essential in meeting emerging energy efficiency benchmarks. By addressing scalability and accuracy issues now, Kepler can position itself as a cornerstone for sustainable operations in high-demand environments [2][4][7].

- Energy Benchmarking for 6G: Next-generation networks, including 6G, will require stringent energy efficiency benchmarks [6]. Kepler's ability to monitor and optimize energy consumption will be pivotal in helping telecom operators and data centers meet these future requirements [2].
- Expanded Metrics for NextG: Kepler can also evolve to support more granular sustainability KPIs, which are essential for guiding long-term resource optimization in NextG ecosystems [2][6]. This would ensure that Kepler remains relevant and practical in future-proofing ICT infrastructures [7].

Blockchain for Sustainability Compliance: Blockchain technology presents an opportunity to enhance Kepler's role in sustainability compliance. By providing immutable records of energy transitions, blockchain could validate renewable energy usage and ensure transparency in line with frameworks like the Carbon Disclosure Project (CDP) [4][7]. For example, blockchain can verify energy transitions in a hybrid cloud environment, ensuring precise reporting of renewable energy usage across interconnected data centers. Additionally, blockchain can streamline the tracking of Scope 1, 2, and 3 emissions by maintaining transparent, tamper-proof records of energy sources and consumption. These capabilities directly support sustainability initiatives such as supplier engagement and enhanced accountability for ESG targets, as highlighted in recent industry assessments [7].

Open-Source Community and Collaboration: To address Kepler's current challenges, it's development could benefit from fostering a broader open-source community. By welcoming contributions for advanced AI models, extended platform support, and novel use cases, the project could evolve into a more robust and widely adopted framework. Collaborative efforts could address existing limitations while driving innovation in sustainability-focused cloud-native operations and across industries [1].

Kepler transcends traditional orchestration systems when incorporating advanced AI and refined predictive models, positioning itself as an indispensable tool for organizations striving to achieve long-term sustainability. Whether employed for regulatory compliance or voluntary initiatives, it empowers Telcos and data centers to scale responsibly while aligning operational growth with global environmental imperatives [2][7]. By proactively addressing bottlenecks in current energy monitoring frameworks and emerging demands in current energy monitoring frameworks, Kepler is poised to enhance sustainability within existing ICT ecosystems, drive innovation, and set the standard for energy-efficient operations in the era of 6G and NextG networks [6].

3. Conclusion

Kepler exemplifies a significant advancement in cloud-native operations, aligning sustainability with operational excellence. By leveraging technologies like eBPF, machine learning, and seamless observability integrations, it addresses pressing demands for carbon footprint reduction and global compliance [3][5]. Its flexibility across Kubernetes, hybrid, and multi-cloud environments makes it indispensable for industries aiming to meet ESG goals and operational efficiency [1][4].

Through applications like 5G workload profiling and edge computing, Kepler can address both current energy challenges and the demands of next-generation networks. As organizations strive for net-zero carbon goals, Kepler offers a practical and forward-looking solution, balancing growth with environmental responsibility [3][7].

To maximize its impact, addressing scalability challenges and integrating advanced AI, blockchain, and renewable energy planning will position Kepler as an industry standard for sustainable ICT infrastructures. Whether for compliance or voluntary initiatives, Kepler ensures organizations can scale responsibly while contributing to a greener future.

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