Increasing Transparency and Explainability in Microgrid Systems by Leveraging Procedural Knowledge

Erwin Filtz[1,*], Josiane Xavier Parreira[1]

[1] Siemens AG Österreich

Abstract

Microgrids are composed of heterogeneous devices such as electrical vehicle chargers, batteries and photovoltaic devices. Microgrid operation's management faces significant challenges in transparency, explainability, standardization, and knowledge transfer across different stakeholders, as a large portion of the information about it is undocumented, hidden behind controller' logic and remains within experts. This paper proposes a novel approach using the Procedural Knowledge Ontology (PKO) to model and manage microgrid operations by representing device behaviors as executable procedures. Key innovations include the capture of operational patterns, contextual information, and execution details in a structured format, enabling improved transparency and explainability. In this paper, we present our vision for enabling transparency and explainability of microgrid operations. In particular, we detail how the PKO can describe device operations and procedure execution traces, providing insights into the charging processes for electric vehicle owners. While the current implementation is preliminary and serves as a proof of concept, this research contributes to the standardization of microgrid operations documentation and provides a foundation for improved stakeholder communication, microgrid maintenance and end-user interaction.

Keywords

Procedural Knowledge Ontology, Microgrid, Timeseries, Knowledge Graph

1. Introduction

Microgrids are localized, self-contained electricity networks capable of operating both in connection with traditional power grids and independently. They serve as enablers in the transition towards renewable energy, offering communities and organizations enhanced control over their power generation and consumption patterns.

The complexity of microgrids stems from their heterogeneous composition, incorporating various independently operating devices, including electric vehicle chargers, batteries, and photovoltaic (PV) units. Their operation is governed by multiple dynamic factors: controller rules, usage patterns and environmental variables, like weather conditions influencing the PV production. While these devices generate substantial operational data, the challenge extends beyond mere data storage and analysis. The critical task lies in extracting meaningful insights that can drive microgrid optimization (e.g., [1]). This challenge is further compounded by the fact that essential contextual information about the microgrid, such as specific device configurations, historical performance patterns, local environmental factors, and operational constraints, often exists only as tacit knowledge held by experienced operators. This undocumented expertise, which is crucial for interpreting system behaviors and making informed operational decisions, risks being lost or fragmented, potentially impacting the microgrids long-term efficiency and reliability. Moreover, the lack of formalized contextual knowledge creates significant barriers across different stakeholder groups. For microgrid operators, especially those newly appointed, this knowledge gap hampers their ability to effectively troubleshoot unusual operational patterns or optimize system performance. For end users, such as electric vehicle owners, this lack of transparency limits their ability to make informed decisions about their interaction with the microgrid, such as determining optimal charging times, understanding energy consumption patterns, or adapting their usage

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*Corresponding author.
erwin.filtz@siemens.com (E. Filtz); josiane.parreira@siemens.com (J. X. Parreira)
0000-0003-3445-0504 (E. Filtz); 0000-0002-3050-159X (J. X. Parreira)

behavior to align with grid efficiency. This information asymmetry not only affects operational efficiency but also impacts user satisfaction and trust in the system, particularly when unexpected behaviors occur, for instance the car is not charged as expected.

To address these challenges and enhance transparency in microgrid operations across all stakeholder levels, we propose to use a semantic model for the devices' operations. This approach can capture the relationship between actions, events, and operational states, documenting how different triggers and conditions influence device behavior. The resulting model serves multiple purposes: it enables explainability by providing operators with detailed insights for system optimization and troubleshooting, helps users to better understand and predict system responses, and creates a bridge between technical complexity and practical usability. This enhanced transparency not only improves operational efficiency but also empowers stakeholders to make more informed decisions about their interaction with the microgrid, whether they are technical experts managing the system or end users seeking to optimize their energy usage patterns.

Although microgrids operate in continuous states rather than discrete steps, modeling their operation through procedures offers several key advantages: (i) *State Transition Representation:* Microgrid devices transition between distinct operational states. For example, electric vehicle chargers operate in states such as high charging, low charging, error, or standby. These states and their transition conditions can be effectively captured as procedures, with specific parameters depending on the device type; (ii) *Procedure Execution Tracking:* By modeling operations as procedures, we can systematically track and record their execution, capturing the sequence of events, decisions, and state changes that occur during operation. This execution history provides valuable data for explaining system behavior and troubleshooting operational issues; (iii) *Structured Documentation:* Procedural models provide a systematic framework for documenting system behavior, making it easier for stakeholders to understand and communicate about system operations. This structured approach supports better maintenance and knowledge transfer; and (iv) *Cross-System Standardization:* The procedural approach enables consistent documentation across different microgrids, supporting compliance requirements and facilitating comparative analysis of different installations.

To implement our approach, we leverage the Procedural Knowledge Ontology (PKO) [2], a semantic framework designed for modeling procedures and tracking their execution. The PKO enables us to formally specify operational procedures for microgrid devices, including their states, transitions, and the conditions that trigger changes in operation. Beyond modeling potential behaviors, the PKO also captures the actual execution of these procedures, recording how devices operate in practice. This execution tracking provides valuable data for both real-time monitoring and retrospective analysis of system behavior. By maintaining both the procedural model (what could happen) and execution records (what did happen), the PKO creates a comprehensive framework for understanding and explaining microgrid operations. This combination of procedure specification and execution tracking is particularly valuable for providing transparent explanations to stakeholders about system behavior.

In this paper, we propose a novel approach to modeling microgrid operations by representing device behaviors as executable procedures, with a specific focus on electric vehicle charging processes. Using the PKO ontology, these procedures capture operational patterns, contextual information, and execution details in a structured way that enhances system transparency and explainability. This procedural representation creates a foundation for organizing and communicating operational knowledge to different stakeholders. Our work is still preliminary but it establishes the basis for developing explainable interfaces, including conversational systems like chatbots, that enable users to query and understand microgrid operations through natural language interactions. This approach aims to make complex technical processes more accessible to both operators and end users, providing meaningful insights into microgrid behavior. In addition to the PKO model, we also developed an initial prototype of an application to visualize the procedure executions.

The remainder of this paper is structured as follows: In Section 2 we list some of the existing work related to our approach. Section 3 presents our envisioned system architecture, while Section 4 focuses on how procedure models and their execution records work together to enable transparency and explainability. Using an electric vehicle charging scenario as a running example, we demonstrate how the PKO model captures both the charging procedure and its execution, showing how this information can be used, for instance, to visualize the charging device's behavior. Section 5 concludes with our findings and outlines future research directions.

2. Related work

Related works regarding microgrids have been published in different directions. There have been proposals of ontologies towards increasing the interoperability between the devices which are part of a microgrid, such as OntoMG [3] and SSG [4], providing a framework to overcome the interoperability obstacles coming with heterogeneous devices as well as including external factors, like economy or ecology, that also contribute to the success of a microgrid. Another work [5] in the same direction of fostering interoperability, employs the Common Information Model (CIM) in order to build a microgrid control system. A similar approach of extending the CIM by reusing existing ontologies resulted in the proposal of the ∀Platform [6]. In addition, there also have been standardization activities based on the SAREF [7] ontology, for instance the SAREF4ENER[1] and SAREF4GRID[2] standards extending the SAREF ontology. The SAREF4ENER standard describes a protocol-agnostic set of messages for the exchange of messages between smart appliances. The SAREF4GRID extension provides means to represent information about electric grid meters. Our work currently focus on representing the operation of the microgrid devices, from a procedural point of view, rather than the microgrid topology itself. Nevertheless, grid topology might be relevant in the future, as it can provide useful information regarding the devices operations.

Electric car charging strategies have also been of interest for some time. Earlier works are investigating the benefits for stakeholders, such as grid owners, operators and its customers by optimizing the charging cycles of electric cars [8] or optimizing load profiles by forecasting charging demands to optimize charging procedures [9]. Charging strategies and their impact on the microgrid have also been under investigation for years. Different algorithms to improve the microgrid utilization, reduce power consumption, reschedule charging times and to optimize the battery state of charge have been proposed (e.g., [10, 11]). More recent works also include a sustainability aspect in the analysis to find the optimal microgrid operation mode by integrating information about the use of renewable energy sources in the charging strategies (e.g., [12, 13]). Our idea is to be able to represent and describe how different strategies are executed during the microgrid operation, but combining the knowledge about the strategies with the data observed. By doing so we enable transparency and explainability of the microgrid operation.

Additionally, we also want to mention the Business Process Model and Notation (BPMN)[3], which is used to model business processes. BPMN has already been used to model the workflows and relationships in the energy domain with a focus on the business aspect (e.g., [14, 15]). However, we use the PKO in our use case as it is a better fit: BPMN is more focused on a graphical notation and acting as a stand-alone representation of process without properly capturing semantics. On the contrary, the PKO is an enabler for a richer semantic representation and can be easier integrated with other knowledge bases. Furthermore, it can be extended with already existing ontologies and supports reasoning.

Closest to our approach is the work performed in the SENSE project[4], which explored semantic explainability for cyber-physical systems through use cases in both smart building and smart grid domains. While SENSE primarily focused on explaining specific system events (such as voltage violations) in grid operations, our work takes a different direction by focusing on describing the operational patterns of various grid devices and providing explanations for their behavioral characteristics. Although our approaches differ in scope, our research can significantly benefit from SENSE's contributions, particularly their methods for modeling causal relationships.

[1] https://saref.etsi.org/saref4ener/v1.2.1/
[2] https://saref.etsi.org/saref4grid/v1.1.1/
[3] https://www.omg.org/spec/BPMN
[4] https://sense-project.net

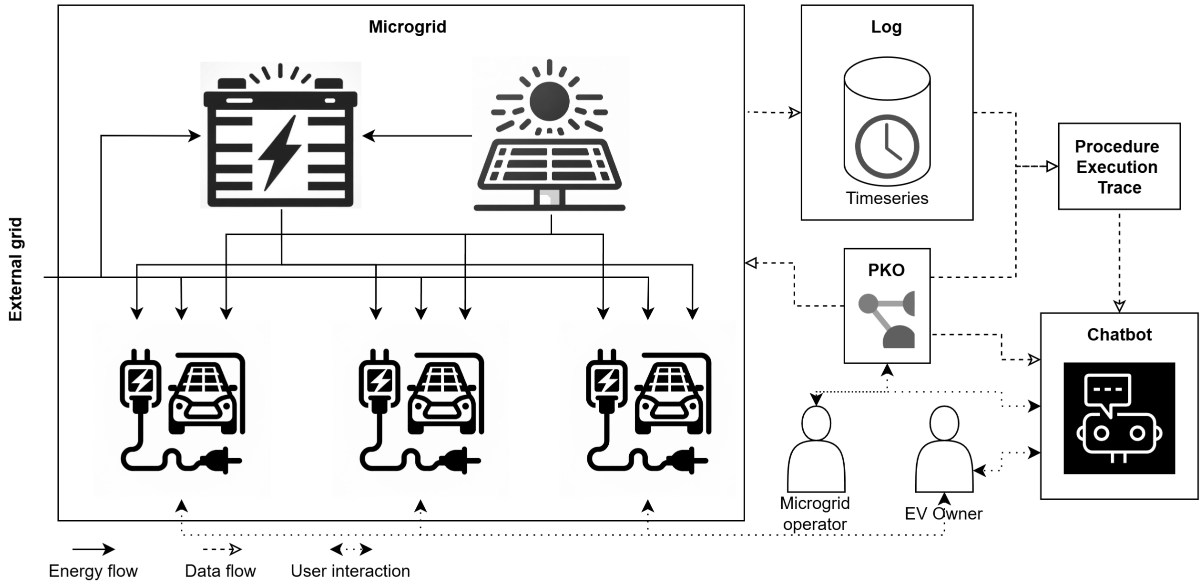

Figure 1: System's architecture for increasing transparency and explainability of microgrid operation.

3. System's Architecture

Our proposed architecture is shown in Figure 1. It includes a standard microgrid setup, which contains electrical vehicle chargers (EVC), a photovoltaic device (PV) and a battery. The EVC are used to charge electric cars, a battery can be charged and discharged on demand in order to store or provide additional energy to the microgrid and a PV provides renewable energy to the grid. In general, the number of devices in a microgrid might vary and some device types might not be present (e.g. PV system) in every microgrid. A microgrid is connected to an external grid to supply the microgrid with energy exceeding the current energy demand. Each device is equipped with its own controller managing the operation of the particular device, and its operation logic is determined by the microgrid operator.

Data from the different microgrid devices are stored in a timeseries database. These include sensor data, such as power output (e.g., watts per phase), charging and cable state (e.g., cable connected to car but (not) charging, no car connected), the power production, and battery state-of-charge. These data enables an ex-post analysis of the microgrid behavior and can serve as input for forecasting algorithms.

In our architecture, the existing microgrid system is extended to include: i) a model of the procedures running at the different devices; ii) a component that combines the log data with the procedural knowledge to create what we call "procedure execution traces"; and iii) a natural language interface, in the form of a chatbot, where users can post queries about the microgrid operation.

As mentioned before, we make use of the PKO ontology to model the devices' procedures. Our goal is to abstract from the low-level sensor data to a higher-level data abstraction that can be explored for explainability. To this end, microgrid operators can specify the steps, or states, of the devices they are interested in, and how to detect them. Moreover, the transition between states can also be recorded, based on the device's controller logic (e.g. if PV production below a certain threshold, switch to a low power charging state). All this information is modeled and stored in a procedure model. Once the model is in place, we can then create a semantic representation of a device's operation. For this we combined the procedural model with the timeseries data to create instances of the execution of the procedure. Currently these instances record when certain steps happened (e.g., start/end time), as well as their occurrence order. We are currently working on extending the model to record additional relevant information, such as the states of nearby devices and weather information. The section below provide concrete examples of the both the procedure model and the procedure execution instances.

While the execution traces alone already provide a more natural understanding of the operation, in

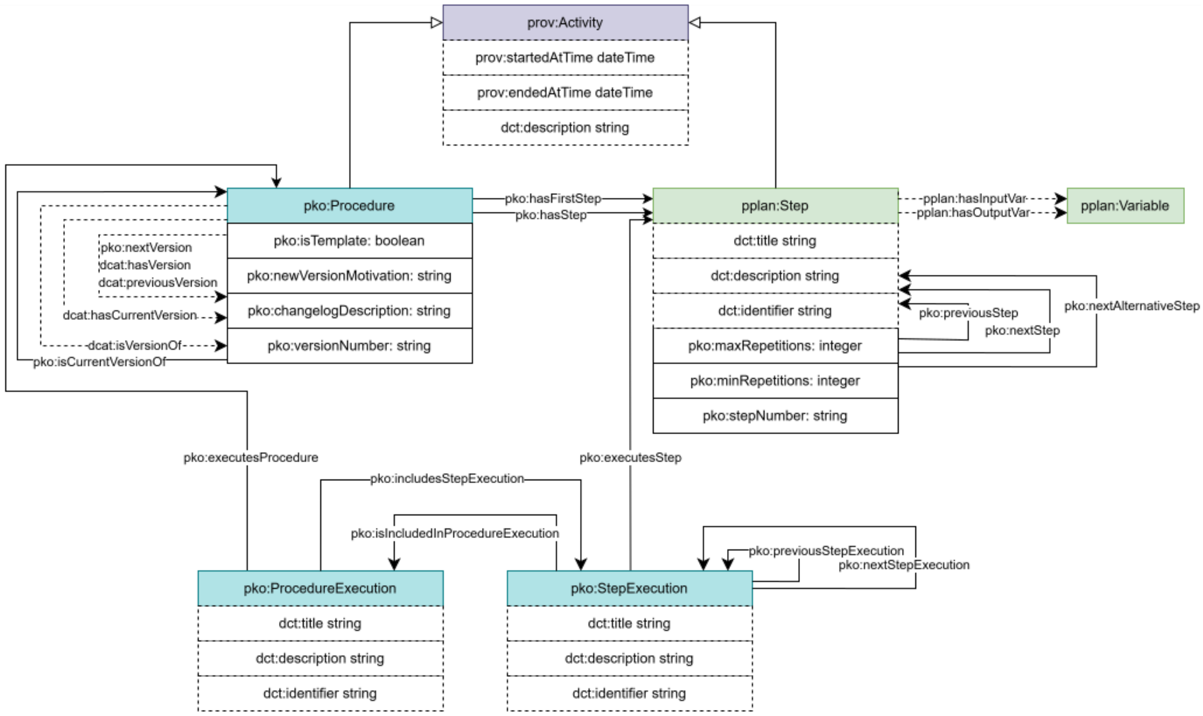

Figure 2: PKO overview with the most important classes and properties used in this paper (based on PKO ontology https://github.com/perks-project/pk-ontology/blob/master/ontology/pko.png)

comparison to the "low-level" sensor data, the main gain of our approach lies on the combination of the traces with the procedure they executed. Through this link, we enhance the information about the microgrid operation with expert, contextual knowledge, otherwise not explicitly recorded.

Both procedural and execution information is available as knowledge graphs and can be currently accessed/queried via standard semantic web interfaces, such as SPARQL endpoints. However, we argue that explainability can be enhanced by the use of the use of "friendlier" natural language interfaces. Recent developments in large language models (LLMs) have transformed how users interact with information [16], making conversational interfaces like chatbots increasingly sophisticated and practical for complex applications [17]. In our proposed architecture the information stored in the knowledge graphs will be accessed via a chatbot by both microgrid operators and EV users, in order to answer questions about the microgrid operation.

After outlining the architecture, we can now present the PKO model for our microgrid. Furthermore, we illustrate how procedure execution traces are generated and showcase an initial prototype of a dashboard that offers intuitive visualization of procedure executions.

4. Procedural knowledge of microgrids

The Procedural Knowledge Ontology provides a robust framework for representation the operation of microgrid devices. It provides classes to describe the procedure (`pko:Procedure`), steps of the procedure (`pplan:Step`) and the relation between steps, which can be sequential (`pko:hasNextStep`) or alternative (`pko:nextAlternativeStep`). Figure 2 illustrates a subset of classes and properties of the PKO, which are the most important for the following examples. A `pko:Procedure` has metadata and contains at least one `pplan:Step`. To illustrate how the PKO ontology can be used in the microgrid domain, we consider the case of EVC devices and will explain the usage of the PKO with two concrete examples. Listing 1 shows (a snippet) of a procedure for a specific EVC, showing instances of `pko:Procedure` and `pplan:Step`. The procedure `sie:evccharging` is titled "EVC charging procedure" with its creation and modification dates as well as the version number. This information is crucial as PKO supports not

```
# Procedure definition
sie:evccharging a pko:Procedure ;
dcterms:created "2025-03-07T12:56:34.297000+00:00"^^xsd:dateTime ;
dcterms:modified "2025-03-07T12:57:59.845000+00:00"^^xsd:dateTime ;
dcterms:title "EVC charging procedure"^^xsd:string ;
pko:versionNumber "0.1" ;
pko:hasFirstStep sie:charging-start ;
pko:hasStep sie:charging-full-power, sie:charging-low-power,
    sie:charging-medium-power, sie:charging-start, sie:not-charging .

# Step definition
sie:charging-low-power a pplan:Step ;
dcterms:identifier "charging-low-power"^^xsd:string ;
dcterms:title "Charging Low Power"^^xsd:string ;
pko:nextAlternativeStep sie:charging-full-power,
    sie:charging-medium-power, sie:not-charging .

# Explanations
sie:low-medium a pko-siemens:Explanation ;
dcterms:created "2025-03-07T14:08:11.014000+00:00"^^xsd:dateTime ;
dcterms:modified "2025-03-07T14:09:31.516000+00:00"^^xsd:dateTime ;
dcterms:title "Charging power increased as PV is producing power"^^xsd:string ;
sie:fromStep sie:charging-low-power ;
sie:toStep sie:charging-medium-power .
```

Listing 1: Excerpt of an EVC charging procedure and one step using PKO.

only the versioning of procedures to track the evolution over time, but also timestamps to document the creation and modification dates. This is particular useful for microgrid operators to record the changes made in the device's controller logic.

The listing also shows the steps which are part of the procedure. In the example we have defined different steps for when the EVC is operating in full, medium or low power, as well as for when there is no active charging activity. To this end we use `pko:hasStep` and the start the first step to be executed at the start of the procedure (`pko:hasFirstStep`) which is `sie:charging-start`. Transitions between steps are part of the step definition as illustrated with the step `sie:charging-low-power`, which defines three alternative next steps (`pko:nextAlternativeNextStep`). That means a EVC can switch between any of the given steps, depending on a number of conditions. In order to later support explainability of the different charging events, we have extended the model to allow for the definition of explanations for transitions between operation modes (i.e. steps). For instance, the transition from low to medium charging due to the PV starting to produce power. Similar to the procedure and step execution, an explanation also contains metadata, such as creation and modification date and a title. This small example shows that knowledge that was previously undocumented and only available as tacit knowledge is formalized and persisted using the PKO. Furthermore, this also eases the validation process of new procedures as multiple experts can have a look into a procedure and change or suggest improvements to it. Additionally, the formalized knowledge enables easier troubleshooting in case of system failures of individual devices as the procedures are available for inspection.

4.1. Procedure execution traces

In contrast to the procedure model, with multiple branches as outlined above, a procedure execution is linear with one step following another step until the procedure is finished. The second example described in Listing 2 shows a snippet of a procedure execution of the EVC charging procedure. The procedure execution contains information about the procedure that has been executed (`pko:executesProcedure`), its current status and when the procedure started and ended. Each step of the executed procedure is linked to the procedure execution. Similarly, a step execution is linked to the procedure execution it is part

```
# Procedure execution
sie:1bf829b9-35dg-98ac-7d1c-dc9fb7b573eb a pko:ProcedureExecution ;
adms:status pko:Completed ;
prov:endedAtTime "2025-01-27T18:42:00+00:00"^^xsd:dateTime ;
prov:startedAtTime "2025-01-27T10:23:00+00:00"^^xsd:dateTime ;
pko:executesProcedure sie:evccharging .

# Step execution
sie:1b758647-5487-4ef4-n67d-7bdc60bdbdbe a pko:StepExecution ;
prov:endedAtTime "2025-01-27T18:42:00+00:00"^^xsd:dateTime ;
prov:startedAtTime "2025-01-27T18:39:00+00:00"^^xsd:dateTime ;
pko:executesStep sie:charging-low-power ;
pko:isIncludedInProcedureExecution sie:1bf829b9-35dg-98ac-7d1c-dc9fb7b573eb ;
pko:nextStepExecution sie:ab78312b-79f3-41b2-9c10-898a2770b007 ;
pko:previousStepExecution sie:1160a809-6dc6-4962-9faf-f6ebf9ebc768 .
```

Listing 2: Execution trace of an EVC procedure.

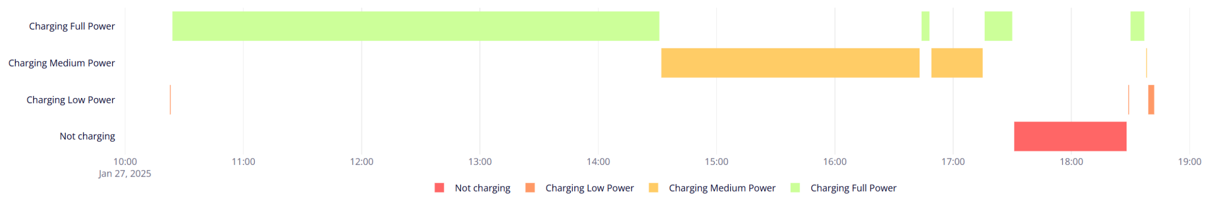

Figure 3: Visualization of procedure execution in a dashboard.

of (`pko:isIncludedInProcedureExecution`) and the step it executed (`pko:executesStep`) and also contains temporal information when the step started and when it ended. Additionally, it is linked to its previous and next step execution enabling an in-detail ex-post analysis of a procedure execution and its steps detailing which branches of a procedure model have been more or less often executed or if there are steps, which are never executed.

The procedure execution traces are automatically generated via scripts combining the procedure model as outlined in Listing 1 and the actual sensor data of the devices from the microgrid.

As already mentioned, representing a procedure and its steps with executions in an knowledge graph manner provides a higher level description of the microgrid operation. However, our end goal is to allow microgrid operators and users investigate and understand what happens during a charging process, without having to be familiar with semantic web technologies such as RDF, SPARQL or knowledge graphs. As a preliminary outcome, we developed a dashboard to analyze procedure executions and represent them visually as shown in Figure 3. The visualization is based on both the procedure model as well as the procedure execution and displays the executed steps in a timeline. The idea behind a graphical visualization of a procedure execution and the involved steps over time is to provide a much more intuitive representation of what happened during a charging process compared to showing data in RDF or tables. Overall, the target is to improve the transparency of the microgrid operation with the procedural model by making tacit knowledge explicit about how the microgrid should behave and to enhance the explainability of what and why something particular happened throughout the procedure execution by the execution traces.

5. Conclusion

The use of the Procedural Knowledge Ontology in microgrid operations significantly improves the management possibilities of microgrids, enhancing transparency and enabling explainability of the microgrid operation. Our work introduces a novel application of the PKO ontology model to represent and analyze microgrid operations, providing valuable insights for both electric vehicle owners and microgrid operators. The main benefit is that this allows us to persist implicit expert knowledge in a structured way. By modeling, analyzing and learning from procedures and their executions, we enhance the reliability, efficiency, and sustainability of microgrids. Our implementation demonstrates that while microgrids operate in continuous states, the discrete procedural representation provides valuable insights into system behavior and facilitates better operational understanding.

The paper also presented our envisioned architecture for enable transparency and explainability in microgrid operations. While our current implementation demonstrates the viability of PKO for microgrid operations, several promising research directions are available for further investigation. We are actively working on integrating and improving a chatbot service that leverages the insights from our models and data to provide users with a more accessible and user-friendly way to interact with the system.

Moreover, we plan to expand our work to incorporate additional microgrid-related information by leveraging existing ontologies mentioned in the related work. This integration will provide a more comprehensive operational view and enable more sophisticated analysis capabilities. Furthermore, we consider sustainability important for future development, such as the incorporation of environmental factors into charging strategies. Specifically, we are planning to investigate the potential for including the impact of CO2 output of different car charging procedures, enabling optimization of charging patterns based on the environmental impact. This enhancement aligns with broader sustainability goals while maintaining operational efficiency.

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Declaration on Generative AI

During the preparation of this work, the authors used Claude Sonnet 3.5 in order to: paraphrase and reword, improve writing style, and grammar and check spelling. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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