

CoupleIT!

Coupling Energy Grids and Research Disciplines

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Abstract – The dtec.bw project *CoupleIT! – IT-based sector coupling: Digitally controlled fuel cell and electrolyzer technologies for stationary and mobile applications* is an interdisciplinary approach to combine a wide range of competencies from disciplines as varied as electrical power systems, economic and social sciences, computer sciences and networks as well as sustainable development and social acceptance research. As such, this article is composed of individual contributions, constituting the main chapters that showcase general approaches and motivations but also concrete results.

This compendium article starts in with a delineation of the motivation behind research in so-called microgrids composed of fuel cell and electrolyzer components and a presentation of the microgrid architecture opted for in this project. Chapter two goes into more detail on the side of electrical engineering and the feasibility of a parallel operation of inverters in microgrids to achieve the ability for an upscaling. Chapter three highlights economic and technological factors for an economically viable and grid-maintaining deployment of a hydrogen-based energy system. In addition, degradation of Li-ion batteries is discussed against the background of their flexible operation in a microgrid and other scenarios. Chapter four grants a glimpse into the field of computer science and the possibility to use artificial intelligence and neural networks for a new way to simulate the behaviour of matter on atomic and molecular scales. This approach holds potential to increase the efficiency of fuel cells by improving the molecular design of fuel cell membranes used within this project. Chapter five elucidates the intricacies of secure communication within one but also between multiple microgrids, an important aspect for achieving a resilient system. Chapter six concludes this compendium by highlighting the human perspective seen from the field of psychological acceptance research nested in the broader context of sustainable development. Among other

things, areas of potential barriers to a public acceptance of hydrogen technology are identified and ways to overcome those barriers proposed.

This interdisciplinary round trip starts with electrical engineering (chapters one and two), economic and social sciences (chapter three), followed by computer sciences (chapter four) and computer networks (chapter five) whence the baton is passed for one last time to the field of sustainable development and psychological acceptance research (chapter six).

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CHAPTER ONE

PEM Fuel Cell-Based Microgrids: Advantages and Future Prospects

by Kazem Pourhossein and Edgar Diego Gomez Ancas

Abstract – Microgrids can provide reliable power supply by operating independently of the main grid during outages, ensuring continuous electricity for critical infrastructure and services. PEM (proton exchange membrane) fuel cell-based microgrids are gaining attention as a reliable, efficient, and environmentally friendly energy solution. In this paper, structural components, advantages, challenges, and future outlooks of PEM fuel cell microgrids are addressed.

Keywords – PEM fuel cells, microgrids, energy storage

I. INTRODUCTION

Microgrids, as localized energy systems, have the potential to revolutionize the way we generate and distribute electricity. PEM fuel cell-based microgrids offer numerous benefits, including high efficiency, low emissions, and reliable power supply.

The concept of fuel cells dates back to the 19th century, but significant advancements in PEM fuel cell technology occurred in the mid-20th century, particularly during NASA's space programs. PEM fuel cells were used to provide clean and reliable power for space missions, proving their viability in demanding applications.

The application of PEM fuel cells in microgrids is a more recent development, driven by the increasing demand for clean energy solutions and advancements in fuel cell technology. Microgrids incorporating PEM fuel cells have been deployed in various sectors, including residential, commercial, and industrial, showcasing their versatility and effectiveness.

II. STRUCTURE AND COMPONENTS OF PEM FUEL CELL-BASED MICROGRIDS

PEM fuel cells are the core power-generating units in these microgrids. They operate by converting hydrogen and oxygen into electricity, water, and heat through an electrochemical process. Key components of PEM fuel cells include the anode, cathode, electrolyte membrane, and catalyst layers.

Hydrogen supply is critical for the operation of PEM fuel cells whereas the necessary oxygen can be supplied by air. Hydrogen can be produced through various methods, including natural gas reforming and water electrolysis. Storage and distribution systems ensure a steady supply of hydrogen to the fuel cells.

Energy storage systems, such as batteries and supercapacitors, are integrated with PEM fuel cells to store excess energy for later use. These systems enhance the reliability and stability of the microgrid by providing backup power during peak demand or outages.

Power electronics, including inverters and converters, manage the flow of electricity between fuel cell units, storage systems, and loads. Advanced control systems monitor and optimize the operation of the microgrid, ensuring efficiency and stability.

A possible power electronics scheme for a laboratory-scale stand-alone PEM fuel cell system is depicted in Figure 1.

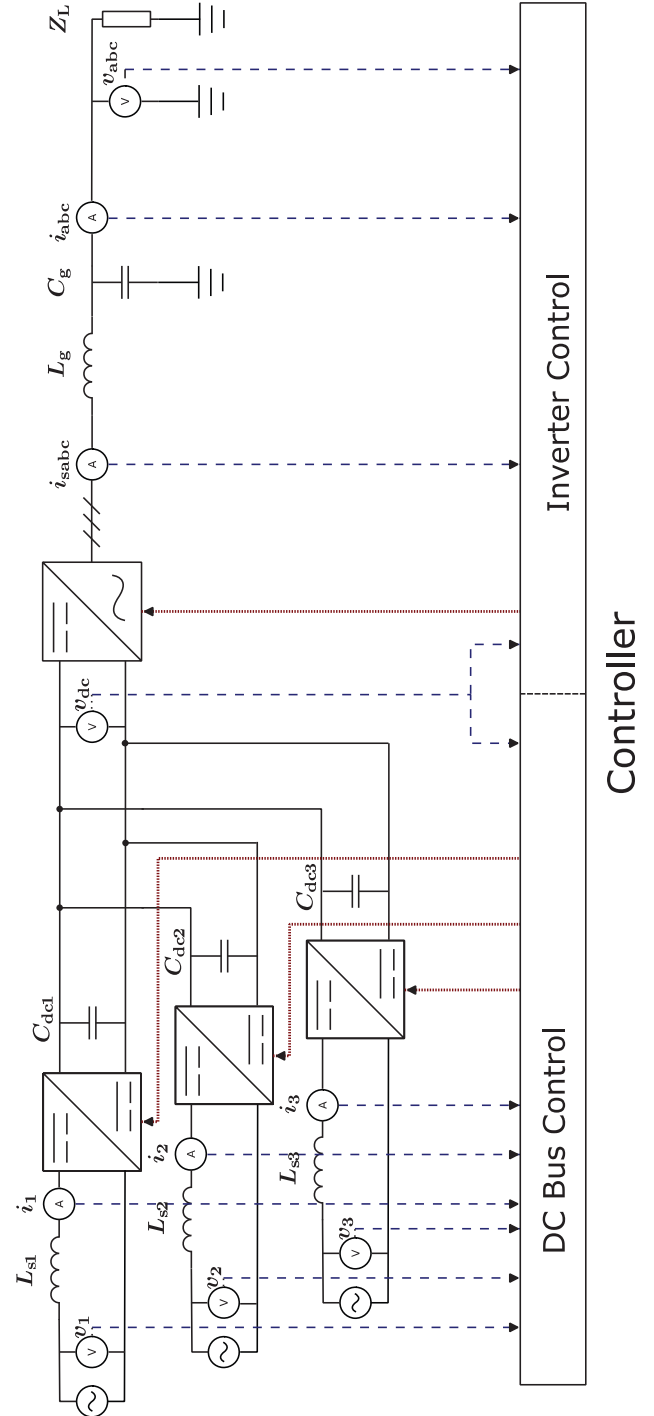


FIGURE 1: A LABORATORY-SCALE STANDALONE PEM FUEL CELL SYSTEM [1]

III. ADVANTAGES OF PEM FUEL CELL-BASED MICROGRIDS

PEM fuel cells exhibit high electrical efficiency and can be integrated into Combined Heat and Power (CHP) systems, utilizing waste heat to further increase overall efficiency. When using pure hydrogen, PEM fuel cells produce only water and heat as byproducts, resulting in zero emissions of greenhouse gases and other pollutants. This makes them a clean and sustainable energy solution. PEM fuel cells provide a consistent and reliable power supply, with fewer moving parts leading to lower maintenance requirements as compared to more conventional systems based e.g. on internal combustion engines. Their durability and longevity make them a dependable choice for various applications. PEM fuel cell systems are modular and can be scaled to cover a broad spectrum of power demands, from residential to industrial applications. The operation of PEM fuel cells is silent, making them suitable for use in noise-sensitive environments such as residential areas, hospitals, and schools. By generating power locally, PEM fuel cell microgrids reduce dependence on centralized power plants and improve energy security. They enhance the resilience of the energy supply, particularly in remote areas or those prone to suffer from natural disasters. Performance analysis of existing projects highlights the efficiency, reliability, and environmental benefits of PEM fuel cell microgrids.

IV. CHALLENGES AND LIMITATIONS

A. Technical Challenges: Technical challenges include hydrogen production and storage, durability, and lifespan of PEM fuel cells. Addressing these challenges requires ongoing research and development [2].

B. Economic Considerations: The cost of fuel cell technology remains a significant barrier to widespread adoption. Comparing the costs of PEM fuel cell microgrids to other energy solutions is essential for evaluating their economic viability.

C. Regulatory and Policy Issues: Current policies and regulations can either support or hinder the adoption of PEM fuel cell microgrids. Identifying and addressing regulatory barriers is crucial for promoting the growth of this technology.

V. FUTURE OUTLOOK

A. Technological Advancements: Ongoing research and development are expected to improve efficiency, durability, and cost-effectiveness of PEM fuel cells. Innovations in fuel cell design and materials will drive technological progress.

B. Market Trends and Predictions: The market for PEM fuel cell microgrids is ready for growth, driven by an increasing demand for resilient and sustainable energy solutions. Emerging markets and applications will further expand the reach of this technology.

C. Policy and Regulatory Support: Governmental incentives and subsidies, as well as international collaborations and standards, will play a vital role in supporting the adoption of PEM fuel cell microgrids. Policy support is essential for overcoming economic and regulatory challenges.

VI. CONCLUSION

PEM fuel cell-based microgrids represent a versatile and sustainable energy solution with significant advantages in efficiency, emissions, and reliability. With continued technological advancements and supportive policies, these systems will

play a significant role in the future energy landscape, contributing to a more resilient and cleaner power infrastructure.

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CHAPTER TWO

Parallel Operation of Inverters in Islanded Microgrids

by Dalia Salem

Abstract – An important goal of the project is to use the gained insights to engage in the modelling of an upscaled and extended version of the microgrid. After successfully initiating, operating, and analysing the single-sourced microgrid in steady-state and dynamical operation, the next step includes the stable operation of multiple sources connected in parallel. In the here applied scenario, two inverters connected in parallel in an islanded microgrid are investigated. The main inverter is generalized droop-controlled and grid-forming, while the second inverter is phase-locked, loop-based, and grid-following. Both are operated isolated from the main grid and supply a local load.

Keywords – *Grid-forming inverter, grid-following inverter, (generalized) droop control, phase-locked loop*

NOMENCLATURE

GFM	Grid-forming
GFL	Grid-following
V_q	Quadrature Voltage Component
PI	Proportional Integral
PLL	Phase-locked loop

I. INTRODUCTION

The first experiment consists in establishing a microgrid with a single source feeding a local load. The microgrid can be operated either in islanded mode, i.e. with no support from the main grid, or in a mode where it follows the main grid and benefits from the latter's grid-supporting capabilities. The islanded mode was investigated first, and a grid-forming (GFM) inverter was set up that supplied a load bank. This system was tested in two operating conditions: steady-state and dynamic operation. The latter featured sudden load jump and load shedding as well as load imbalances in the three phases. The second experiment looked at two inverters connected in parallel. Their synchronization was evaluated and the interaction between the two controllers was analysed.

II. FIRST EXPERIMENT: GRID-FORMING INVERTER IN AN ISLANDED MICROGRID

The laboratory experiments illustrate a solid operation of the microgrid under steady-state conditions, but it collapses upon sudden changes in operational condition. During steady-state operation, the microgrid generates and sets voltage, frequency, and phase angle of the coupling point even in isolation from the main grid. The same control structure can be implemented when the microgrid is connected to the main grid, in which case the inverter follows and supports the main grid.

A. Grid-Forming Inverter and Droop Control Technique

The experiment was about the ability of the GFM inverter to operate independently from the main grid. The inverter generates and sets voltage and frequency of the microgrid within

the accepted boundaries [1], when the microgrid is autonomously operated. The implemented controller has to take into account the technical limitations of the inverter, while being able to detect islanded and grid-connected mode and adapt its performance accordingly. The capabilities of the controller have to include black start, DC offset isolation, post-fault recovery, and parallel operation of inverters.

III. SECOND EXPERIMENT: PARALLEL OPERATION OF GRID-FORMING AND GRID-FOLLOWING INVERTERS IN AN ISLANDED MICROGRID

A. Generalized Droop Control Technique

An inverter governed by a generalized droop control is more robust to sudden changes and disturbances than its counterpart under a classic droop control regime [1]. The former leverages the flexibility of a grid-forming inverter for parallel connection to other inverters in an islanded microgrid and allows of more individual control over each single phase of the system with the required state feedback control.

B. Grid-Following Inverter and Phase-Locked Loop-based Controller

A grid-following (GFL) inverter functioning as a current source, requires a reference voltage source to establish its terminal voltage for operation. The implemented phase-locked loop (PLL) control achieves rapid phase angle detection. The proportional integral (PI) controller within the PLL drives the quadrature voltage component (V_q), thereby providing the angular speed values required to latch and lock onto the phase angle of the voltage vector at the point of common coupling (PCC) thus achieving synchronization.

IV. SYNCHRONIZATION

Examining synchronization is a fundamental step for understanding the dynamic behaviour of microgrids. One key metric to judge the stability of a grid is its frequency. According to [2], the frequency of systems with no synchronous connection to a broader grid, e.g. supply systems on islands, shall stay within the following boundaries: 50 Hz \pm 2 % (i.e. 49 Hz... 51 Hz) during 95% of a week; 50 Hz \pm 15 % (i.e. 42.5 Hz... 57.5 Hz) during 100% of the time". Experimental parallel operation is carried out according to IEEE Std 2030.8-2018 [3].

Figure 1 illustrates a comparison between two conditions, the unsynchronized connection between the two inverters when connected in parallel compared to a healthy synchronized parallel connection achieved through harmonized interconnection between the two controllers.

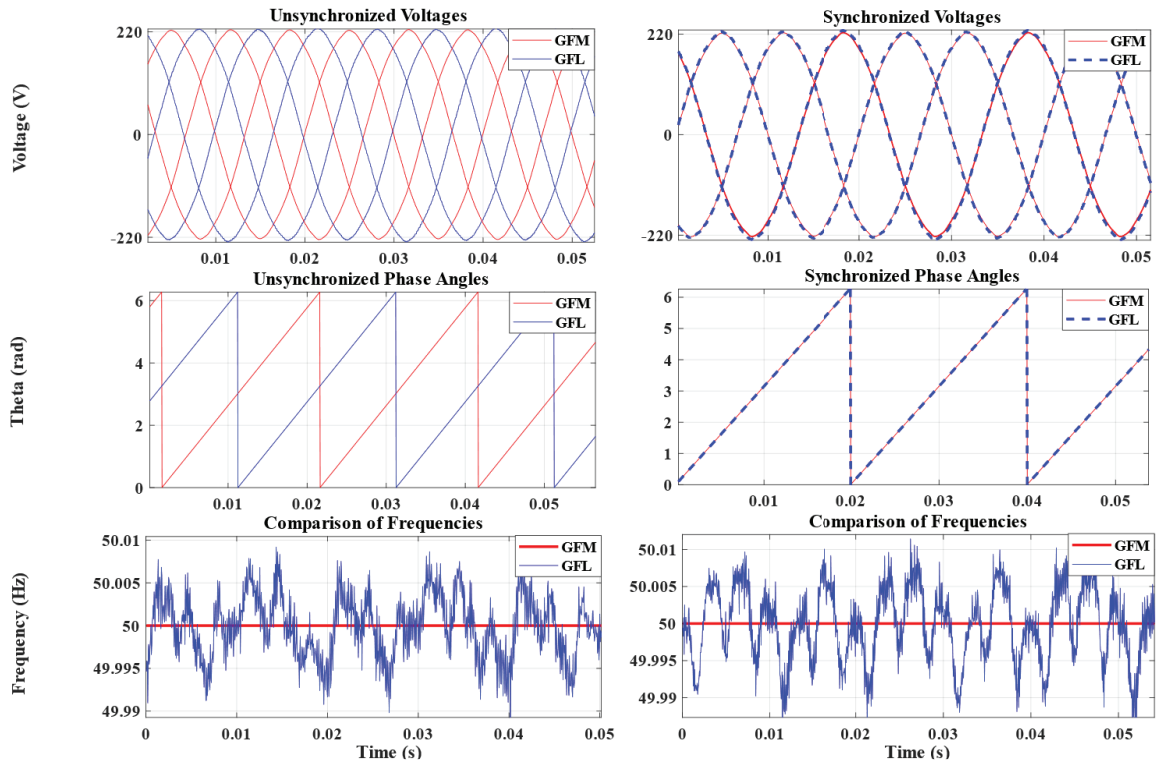


FIGURE 1: COMPARISON OF UNSYNCHRONIZED (LEFT) AND SYNCHRONIZED (RIGHT) OPERATION OF VOLTAGE (TOP), PHASE ANGLE THETA (MIDDLE), AND FREQUENCY (BOTTOM) OVER A PERIOD OF 50 MS

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CHAPTER THREE

Optimal Operation of Li-ion Batteries in Microgrids
and other Scenarios

by Simon Sassen

Abstract – The flexibility in energy provision and consumption that lithium-ion batteries and hydrogen-based energy systems offer, plays a key role in the widespread roll-out of renewable energies. Economic optimization of hydrogen systems must consider technical as well as economic objectives. In this contribution, three aspects of hydrogen systems are elucidated. First, the use of hydrogen in a household is investigated. The aim is to reduce the end consumer costs for electricity by converting hydrogen into electricity using a flexible price tariff. The used method is a linear optimization model for energy storage scheduling. Second, the further goal to reduce peak loads is added to the cost reduction incentive. To this end, the model of the first article is extended to include shiftable loads. Li-ion batteries and hydrogen systems consisting of electrolyser and fuel cell can act as consumers and producers of electricity. The employed method is a bicriteria mixed-integer linear optimization model. It has been shown that costs can be reduced when load smoothing is a priority. Third, an optimal operational management of Li-ion batteries is pursued. The key factors to find a trade-off between drawbacks from battery degradation and benefits from flexible operation are defined. A sequential decision problem is proposed to solve the non-linear characterization of degradation.

Keywords – Microgrid, energy scheduling, demand side management, peak load reduction, cyclic and calendar battery ageing, state of health

NOMENCLATURE

PV	Photovoltaic
RE	Renewable energy
LP	Linear program
MILP	Mixed-integer linear program
NMC	Nickel manganese cobalt battery
SoH	State of Health
SoC	State of charge
DoC	Depth of cycle

I. OPTIMAL ENERGY SCHEDULING FOR A MICROGRID WITH BATTERY AND HYDROGEN STORAGE

In [1] we investigate the suitability of a hydrogen system from the perspective of an end consumer. Although the feed-in tariff decreases from year to year, a photo voltaic (PV) system, despite its significant investment costs, is often still a viable option to reduce the electricity consumption from the public grid and thus the electricity costs to the end consumer. However, due to the fluctuation of renewable energy (RE), energy storage systems are necessary. However, while energy storage systems increase the degree of self-sufficiency, they do also increase the electricity generation costs. For example, the use of hydrogen as an energy storage medium by operating fuel cell (gas-to-power) and electrolysis units (power-to-gas)

introduces unavoidable energy conversion losses. Nonetheless, legislation that creates tax reduction or elimination schemes can help to compensate for monetary drawbacks in the case that hydrogen is converted back into electricity.

In here, we delineate a linear program (LP) that optimizes the deployment of battery, electrolysis and fuel cell units for within the frame of the fluctuating EPEX Spot exchange (see the example in Figure 1) [1]. It has been shown that a hydrogen storage system is usually not a profitable investment at least for a private household. Despite tax breaks for hydrogen reconversion into electricity (fuel cell), flexible trading on the electricity exchange and the increased degree of self-sufficiency mostly do not make up for the investment costs for a household. Instead, it is more worthwhile to sell the hydrogen produced directly instead of reconverting it into electricity [1].

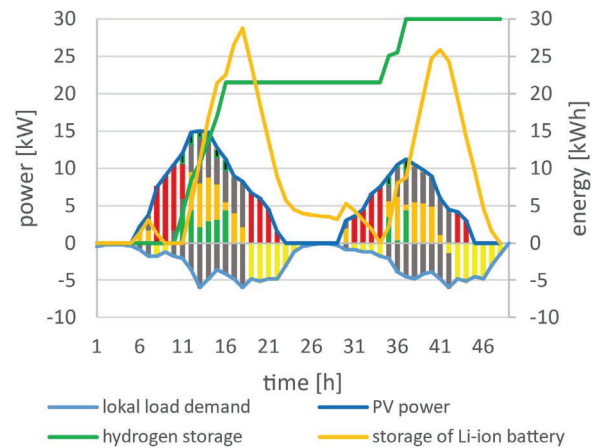


FIGURE 1: ENERGY SYSTEM WITH DEPLOYMENT PLANNING OF THE HYDROGEN SYSTEM AND THE LI-ION BATTERY [1]

II. LOAD SMOOTHING OF A MICROGRID WITH TWO STORAGE SYSTEMS AND SHIFTABLE LOADS

In [2] we study the impact of the use of energy storage and demand-side management (DSM) on instabilities in a microgrid. These instabilities are defined here as the imbalance of supply and demand of electricity. The energy storage units are a battery and a hydrogen system, which can be used as electricity consumers or producers at any one time. The DSM is realized by shiftable loads, whereby a distinction must be made between interruptible and non-interruptible. The proposed mixed-integer linear program (MILP) optimization model addresses the scheduling of shiftable loads and energy storage. The objective is to minimize a weighted sum of the two target variables profit and imbalances. Since these are often conflicting goals, a factor a is used to determine how strongly profit-oriented and how strongly imbalance-minimizing the result should be. In order to reduce load peaks, the imbalances were additionally assessed with a penalization factor.

The higher the imbalance, the higher this factor. The result is a comparison between two scenarios. The first result is yield-oriented without shiftable loads. The result for the second scenario is imbalance-oriented with shiftable loads [2]. Figure 2

shows the deployment plan for electricity consumers and producers for the second scenario. It has been shown that in the second scenario, the maximum imbalances and costs are reduced slightly, while the minimum imbalances and the sum of the amounts of all imbalances are reduced considerably [2].

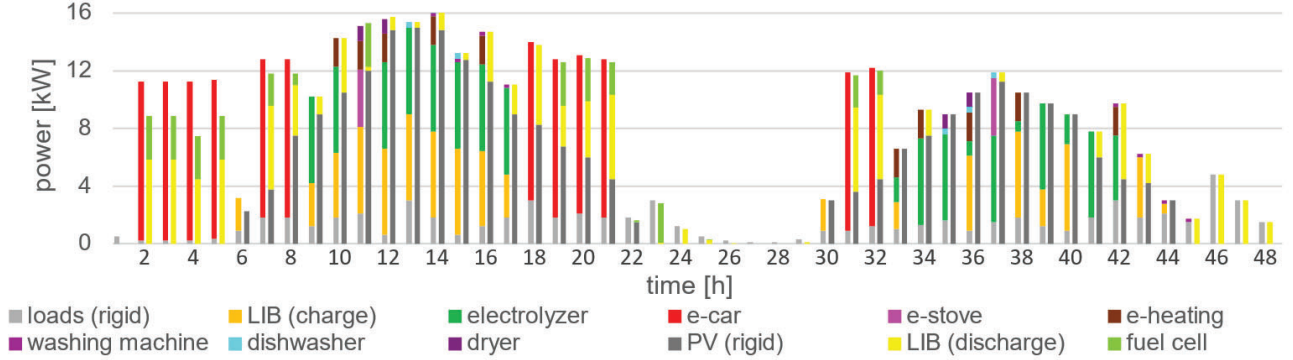


FIGURE 2: ARRANGEMENT OF RIGID AND FLEXIBLE ELECTRICITY PRODUCERS AND CONSUMERS [2]

III. AN OUTLOOK INTO OPTIMAL DIMENSIONING OF A LI-ION BATTERY TAKING INTO ACCOUNT CALENDER AND CYCLIC DEGRADATION EFFECTS DURING DYNAMIC OPERATION

The initial cost of an energy system has a significant impact on the profitability of the entire system. It is therefore important to improve the amortization of the components.

Batteries are subject to calendar and cyclic degradation effects, which reduce the usable capacity or ‘state of health’ (SoH) of the batteries. The level of cyclic degradation depends on many influencing factors, which vary depending on the battery's operating strategy. Since a battery is usually used until a certain SoH is reached, the maximum number of cycles, and therefore battery life, is highly dependent on the operating strategy. For example, low power usage relative to total capacity results in less degradation than high power usage. However, increasing the capacity in order to keep this ratio low also in high power usage scenarios results in higher acquisition costs and calendar degradation that affects the entire capacity from the start. In addition, it may make economic sense to accept increased degradation when exchange rates fluctuate.

Although the degradation of Li-ion batteries has already been examined in an economic context in the literature, there is still a need for further research. The effects of dynamic operation of the battery on overall degradation, considering the large number of influencing factors, have not yet been sufficiently recorded in an economic context. The aim of ongoing work is to model and optimize the dynamic operation of batteries with different capacities. Both calendar and cyclic degradation effects, fluctuating electricity market prices, and optimal battery sizing are to be considered. The non-linearity of the degradation and the uncertainties are formulated and optimized in a sequential decision problem.

The used battery degradation model is based on [3]. According to this model, the total degradation D_{cell} is constituted by calendar and cyclic degradation (formula (1)). The calendar degradation is described as a function of the temperature ($Temp$), the state of charge (SoC) and the time (t) (formula (2)). The cyclic degradation depends on the mean SoC (M_{SoC}), the depth of cycle (DoC), the $Crate$ and the energy flow

($AH_{\text{thp}}^y(N)$) as a function of the number of cycles performed (N) (formula (3)) [3].

$$D_{\text{cell}} = D_{\text{cal}}(Temp, SoC, t) + D_{\text{cyc}}(DoC, M_{SoC}, Crate, N) \quad (1)$$

$$D_{\text{cal}}(Temp, SoC, t) = \alpha(Temp, SoC) * t^{0.5} \quad (2)$$

$$D_{\text{cyc}}(DoC, M_{SoC}, Crate, N) = \beta(DoC, M_{SoC}) * EXP\left(\frac{\rho_{AH}}{112} * Crate\right) * AH_{\text{thp}}^y(N) \quad (3)$$

In a first step, the degradation functions $\alpha(Temp, SoC)$ and $\beta(DoC, M_{SoC})$ of the nickel manganese cobalt battery (NMC) are calculated. In the next step, formulas (2) and (3) are expressed as a function of time and only of the charging, discharging power, and capacity during a period to enable scheduling. These formulas are to be employed in an optimization approach that examines efficient battery usage patterns for different application scenarios.

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CHAPTER FOUR

Towards Practical Neural Network Accelerated High Accuracy Molecular Simulations at Scale

by Tim Rensmeyer

Abstract – Due to the computational complexity involved in first-principles simulations of molecular and material dynamics, the prediction of interatomic forces with neural networks has become an active area of research. An important open question in this domain is how to efficiently generate training datasets to train such neural networks in the first place. As a solution to this, we here propose an approach that utilizes Bayesian statistics and on-the-fly fine-tuning of pre-trained models.

Keywords – Molecular dynamics, neural networks, Bayesian learning

I. INTRODUCTION

Even though the prediction of chemical and material properties such as catalytic activity from first principles has theoretically been possible since the discovery of the equations of quantum mechanics in the 1920s, it remains a challenging task to this day due to the computational complexity involved in solving these equations numerically [1]. This makes the prediction of the time evolution of molecular systems – Molecular Dynamics (MD) – challenging from first principles since the forces acting on each atom have to be calculated at each time step. Consequently, even with the workhorse quantum chemical simulation method Density Functional Theory (DFT), simulations are only possible with a limited time horizon and system size [2]. As a response to these challenges substitutional modelling of molecular dynamics via neural networks has become an active area of research [3]. State-of-the-art neural network architectures have by now achieved unprecedented accuracy and data efficiency in the prediction of atomic forces and energies on small molecule benchmarks [4] where the training data has been subsampled from molecular dynamics simulations that are temporally long enough for the molecule to have traversed its configuration space exhaustively. However, while such benchmarks are very useful for the determination of suitable neural network architectures, they do not represent a realistic scenario of how a neural network-based force field would be used in practice by computational chemists or material scientists. The reason for this is that if it is possible to simulate such an exhaustively long MD trajectory with classical quantum chemical simulations, the neural network model would not be needed in the first place. The application scenarios where a substitutional neural network model would be the most valuable are those where classical simulations do not allow for a sufficient time horizon to be simulated and where it is not known beforehand, what atomic configurations the system might traverse.

II. SOLUTION APPROACH

To make neural network accelerated molecular dynamics simulations of fuel cell components (i.e. polyelectrolyte membranes, catalysts) possible, the professorship of computer science in mechanical engineering at the HSU Hamburg is developing a Bayesian neural network framework to integrate large-

scale public materials databases, uncertainty quantification and classical quantum chemical simulations into an efficient on-the-fly learning approach. We want to utilize the large-scale material databases of different molecular configurations with force labels to construct an informative Bayesian prior density over the weights of the parameters of the neural network. This prior density will be iteratively refined via Bayes' rule based on new data from the specific system that is supposed to be simulated. In this approach, the Bayesian neural network drives the molecular dynamics until an atomic arrangement is encountered for which the uncertainty in the prediction is above a certain threshold. At this point, a classical DFT simulation will be called into action to calculate the forces in that configuration. Based on these calculated forces, the Bayesian neural network will be updated and then resume driving the molecular dynamics simulation until again a configuration above the uncertainty threshold is met (Figure 1).

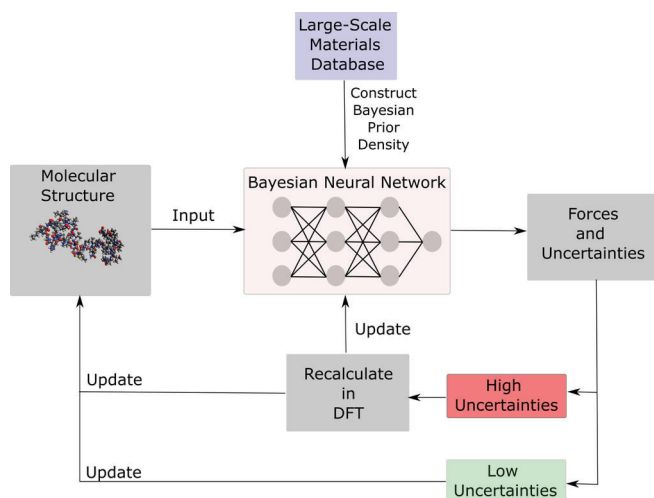


FIGURE 1: ILLUSTRATION OF THE ON-THE-FLY LEARNING APPROACH TO ACCELERATE MOLECULAR SIMULATIONS

The development of that framework requires three key steps.

First, a suitable Bayesian neural network model has to be created based on state-of-the-art neural network architectures. The practical viability of this network has to be verified with a focus on viability of sampling the Bayesian posterior, model accuracy, and quality of uncertainty quantification.

Secondly, a suitable Bayesian prior to incorporate large-scale databases has to be identified and empirically verified.

Lastly, the Bayesian neural network model and Bayesian prior have to be integrated into an on-the-fly learning workflow (Figure 1).

At his point, the first two steps have been achieved [5], while the last step is being worked on. In the future, we hope to utilize this learning framework to gain insights into the molecular processes of fuel cells at quantum mechanical accuracy.

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CHAPTER FIVE

Decentralized Security Monitoring as Enabler for Zero-Trust in Networked Microgrids

by Heiko Bornholdt

Abstract – The transition of power grids to an open, dynamic, and automated system necessitates more advanced security monitoring approaches. This paper proposes a decentralized security monitoring architecture for networked microgrids, implementing a zero-trust security model capable of detecting internal and external attacks. Furthermore, threat intelligence is shared among microgrids to increase the resilience of individual microgrids and the overall power grid.

Keywords – *Microgrid, cybersecurity, security monitoring, anomaly detection*

I. INTRODUCTION

The ongoing opening of power grids, which results in increased participation and the need for more automation and management, not only presents opportunities for enhancing efficiency but also poses risks concerning grid availability.

Power grids transform from a closed static system, characterized by a few large electricity providers, into an open, dynamic, and automated system. This new system includes many decentralized energy sources, prosumers (entities that consume and produce energy), microgrids, and intelligent control technologies. The shift to an open system requires more sophisticated security monitoring approaches for microgrids [1]. Security monitoring refers to the continuous observation and analysis to detect suspicious behaviour or unauthorized changes in the system.

To this end, we define the following requirements for security monitoring in microgrids within modern power grids [2]: **high accuracy** for detecting and responding to threats and anomalies; **scalability** regarding the number of devices within a single microgrid and across multiple microgrids; and **decentralization**, since in an open system other participants cannot be trusted and centralized trusted authorities represent a single point of failure that must be avoided.

This paper proposes a decentralized security monitoring architecture for microgrids. By implementing a zero-trust security model, we make minimal assumptions about the trustworthiness of system entities, such as users, electric systems, or network components. We ensure that all entities and actions undergo strict authentication before processing. This approach enables the detection of threats originating from external sources and within the microgrid while also protecting the security monitoring system itself. Additionally, security monitoring information is shared across microgrids to enhance the overall system's ability to detect and respond dynamically to security threats and anomalies.

II. SYSTEM ARCHITECTURE

Figure 1 depicts our architecture for a decentralized security monitoring of networked microgrids enabling zero-trust

capabilities. The power grid is a hierarchically organized network with large regional network operators (Figure 1 left box, top). Within an operator's network, microgrids are run by third parties (right box). A microgrid is divided into a power network (red arrows) and a communication network (green arrows). Depending on the specific grid configuration, the power network contains several electrical systems that provide, store, or consume energy. These individual systems are managed locally by a first-level controller or monitored by a smart meter. The communication network includes a router connected to the Internet, all first-level controllers, smart meters, and the second-level controller. The second-level controller orchestrates the microgrid by collecting information from and sending commands to first-level controllers and smart meters to optimize the grid's operation towards a defined goal, such as efficiency, reliability, or sustainability. The router's connection to the Internet allows the second-level controller to communicate with a third-level controller of the operator's grid for coordination. To enable zero-trust in this context, we add the following functions to the system.

Network monitoring sensor: This sensor is connected to the router on a monitoring port configured to send a copy of all traffic passing through the router. This enables the sensor to analyse data without impacting network performance. All information between first-, second-, and third-level controllers and smart meters is sensed and acts as the primary source of security monitoring. This also includes messages received from the Internet sent by the third-level controller or third parties, monitoring information from smart meters such as live consumption, commands from the first-level controller, and directives issued by the second-level controller. This information is then forwarded to the security data fabric for further analysis and action.

Security data fabric: The fabric centrally manages and analyses security data received from individual sources and provides a unified view and control. In this context, information is stored, cleaned, transformed, normalized, formatted, or combined with other information to handle missing data. These data wrangling and data engineering tasks are necessary for the next step, the security analysis.

Security analysis: Here, information from the fabric is evaluated to identify vulnerabilities and potential threats. This includes model inference, which applies trained machine learning models to real-time data to detect complex attack patterns and subtle anomalies beyond traditional methods. Anomaly detection uses statistical models and algorithms to identify unusual patterns in data that may signify security threats, providing critical early warnings. Signature-based detection identifies malicious activities by comparing network behaviour against a database of known threat signatures, effectively

recognizing established threats. Once data is analysed, the risk is assessed.

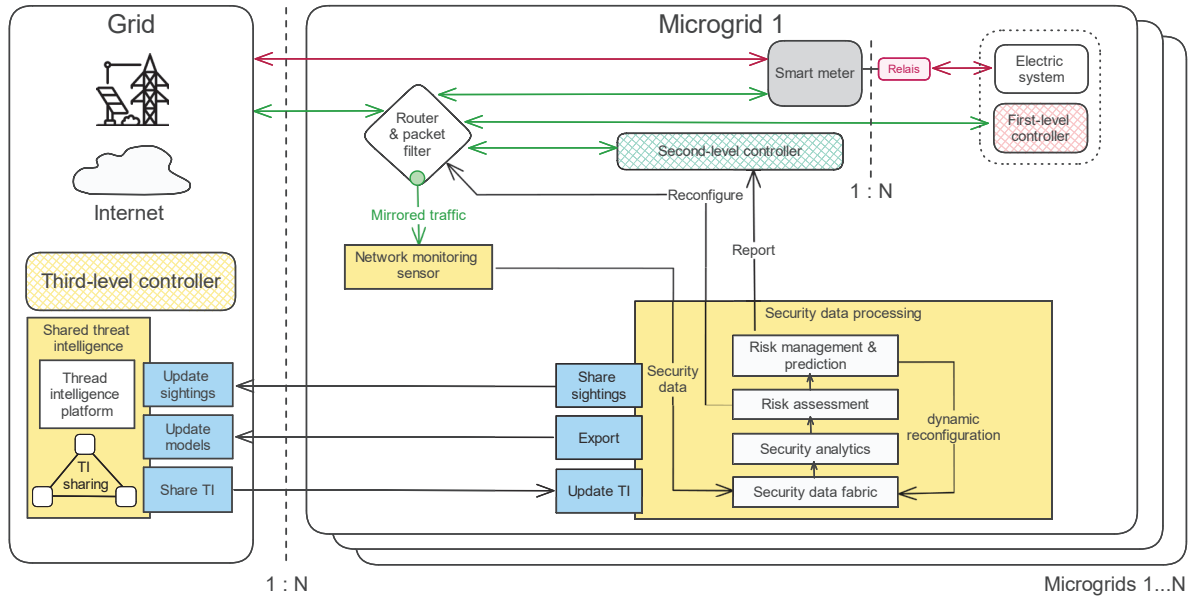


FIGURE 1: ARCHITECTURE OF DECENTRALIZED SECURITY MONITORING IN NETWORKED MICROGRIDS (TI = THREAT INTELLIGENCE)

Risk assessment: Risk assessment quantifies and prioritizes risks by evaluating the potential impact and likelihood of occurrence of identified threats. This process helps determine which vulnerabilities could cause the most damage, guiding the prioritization of mitigation efforts. Two measures can be taken in response to this task:

- The packet filter embedded in the router is reconfigured. This packet filtering can include blocking traffic from specific IP addresses, ports, or protocols identified as sources of malicious activity and permitting only traffic that meets established security policies. This filtering is conducted to prevent unauthorized access and potential attacks and to isolate vulnerable systems from others.
- A report is sent to the second-level controller, which includes information about the identified threat and the countermeasures conducted at the router's packet filter. Using this information, the controller can respond by counteracting on the power network side, for example, by shutting down affected systems and allowing unaffected systems to adapt to this change.

Risk management and prediction: Furthermore, risk management involves implementing strategies and timely measures to mitigate identified risks, continuously monitor their effectiveness, and adapt as necessary. Risk prediction is an aspect of this, forecasting potential future threats and vulnerabilities to address them proactively before they can impact the microgrid. This task may involve reconfiguring the data fabric, for example, to incorporate new protocols or update processing algorithms to improve the unified information view.

Shared threat intelligence: Individual microgrids will share their sightings of potential threats with other microgrids to further improve their threat detection accuracy, allowing them to protect against new attacks and proactively harden the overall grid. To facilitate this, the grid provides a platform for shared threat intelligence, where microgrids can provide their

data and update their local threat intelligence database. The zero-trust model helps by not blindly trusting potentially malicious or infected microgrids, as each microgrid's contribution to the platform is verified first.

III. CHALLENGES AND OPPORTUNITIES

We present an architecture for distributed security monitoring across networked microgrids. Individual microgrids can share their sightings to a centralized threat intelligence platform. Shared information is authenticated and verified before being locally applied, enabling a zero-trust security model. In this context, providing an incentive model that prevents participants from becoming free riders and not contributing to the system will be challenging. In the future, we want to implement a proof of concept to show how our system performs in different scenarios, such as an attack on a single system, multiple systems, or multiple microgrids.

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CHAPTER SIX

Shaping Hydrogen Transformation: Socio-Psychological Insights in Hydrogen Acceptance

by Rubina Shirin Steller

Abstract – Achieving sustainable diffusion of hydrogen technology (HT) necessitates societal engagement and responsiveness to stakeholder concerns. The socio-psychological project at the Integrative Institute for Sustainable Development, part of the dtec.bw CoupleIT! project, emphasizes early stakeholder engagement and systematically analyses factors influencing hydrogen acceptance. Stakeholder interviews with industry leaders in Hamburg identify important perceived prerequisites, barriers, chances, risks, and institutional responsibilities in the context of a hypothetical project involving the implementation of smart integrated grids (SmInT-Grids). Representative surveys are employed to assess theoretical frameworks affecting HT acceptance. Our research underscores the necessity of validating acceptance measures, integrating participation variables, and broadening stakeholder engagement to enhance understanding and practical application of HT acceptance, ensuring a more inclusive and effective transition to sustainable energy systems.

Keywords – Hydrogen technology, acceptance, stakeholder interviews, socio-psychological factors, discourse analysis

NOMENCLATURE

HT	Hydrogen technology
RET	Renewable energy technologies
SmInT	Smart-InTegrated

I. INTRODUCTION

The energy transition requires solutions that are not only technically and economically feasible but also socially accepted. Innovations such as the development of a SmInT-Grid evolve within a complex economic, social, cultural, and political landscape, influenced by the diverse factors inherent in this environment [1]. Acceptance research examines the transition from CO₂-producing systems to renewable energy technologies (RET), focusing on socio-political, community, and market dimensions. These dimensions capture various aspects of stakeholder acceptance, reflecting broader social climates, local community attitudes, and market behaviours [2]. Despite increasing research in this field, end-users are often viewed as obstacles rather than integral contributors to system design, overlooking the essential role of social acceptance dynamics in energy transitions [3].

Within the research project, we emphasize early stakeholder engagement. We systematically analyse socio-psychological factors influencing hydrogen technology (HT) acceptance and investigate how researchers perceive and discuss barriers, drivers, and implications of HT diffusion, highlighting their understanding, focus areas, and potential biases in acceptance research. Engaging stakeholders aims to understand

their perspectives and attitudes, creating a participatory platform for effective communication and deriving recommendations to support sustainable transformation processes.

II. INSIGHTS INTO RESULTS

1) *A Systematic Review of Socio-Psychological Influencing Factors*

Our systematic literature review of 2023, spanning studies from 2004 to 2023 on acceptance research, reveals a predominant focus on upstream phases, with significantly less attention given to downstream research. Upstream research involves the early stages of technology development, including conceptualization and initial implementation, while downstream research pertains to later stages such as widespread adoption and post-implementation effects [4]. However, public perceptions and acceptance are critical throughout the entire technology lifecycle [5], underscoring the necessity for longitudinal studies to capture temporal variations in the acceptance of HT. Significant socio-psychological factors impacting HT acceptance were identified, with environmental attitudes being the most extensively studied. Social trust, showing a positive correlation with HT acceptance, was the second most researched factor. There is a notable interconnection between trust and risk perception, where higher perceived risk leads to diminished acceptance. Additionally, trust and participation in decision-making processes positively correlate with overall acceptance. Other influential factors include affect, knowledge, and social norms. However, our analysis indicates a focus on enhancing acceptance, potentially overshadowing the broader aim of understanding acceptance dynamics [6].

2) *A Stakeholder Analysis on SmInT-Grids*

A comprehensive stakeholder analysis is integral to our research project, involving online face-to-face interviews averaging 59 minutes. We interviewed heads of companies and research institutes, energy suppliers, network operators, and regulatory authorities in Hamburg. This analysis provides insights into stakeholders' perceptions regarding the integration of SmInT-Grids, a previously underexplored area in acceptance research. Our stakeholder analysis revealed various perspectives, of which we present a brief snapshot (due to pending peer-reviewed journal publications, more detailed results cannot be disclosed at this time). Key prerequisites for the potential implementation of a smart integrated grid include effective stakeholder management and knowledge exchange, ensuring investment security, gaining access to suitable construction sites, and establishing an efficient regulatory framework. Stakeholder management, from the perspectives of interview partners, involves regular meetings, information dissemination, and resource management. Transparency in project conditions and investment incentives from governmental bodies were perceived as essential for investment security.

Stakeholders were also asked to consider potential application areas for SmInT-Grids. They identified potential applications such as grid balancing, load peak management, and supplying areas with inadequate grid connections. The grids were considered promising for medium-term balancing, seasonal energy storage, and neighbourhood solutions. However, criticisms included the viability of island grids in urban areas with centralized power systems, high costs, and complexity in maintaining voltage and frequency stability.

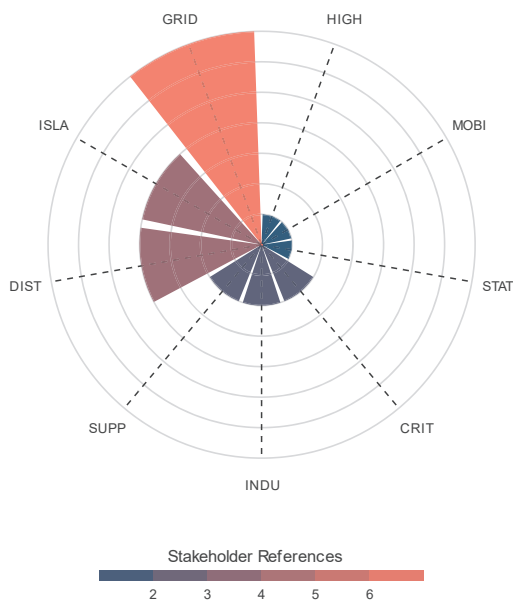


FIGURE 1: SUGGESTED APPLICATION AREAS OF *SMINT-GRIDS* BY STAKEHOLDERS. CRIT = CRITICAL INFRASTRUCTURE (E.G. HOSPITALS, PUBLIC TRANSIT), DIST = DISTRICT ENERGY SOLUTIONS FOR RESIDENTIAL AREAS, GRID = GRID BALANCING/LOAD PEAK MANAGEMENT, HIGH = AREAS WITH HIGH ENERGY INPUT/OUTPUT, INDU = INDUSTRY, ISLA = AREAS WITHOUT GRID CONNECTION (E.G. ISLANDS), MOBI = MOBILE POWER SUPPLY FOR EVENTS, STAT = STATIONARY BACKUP POWER INSTEAD OF DIESEL GENERATORS, SUPP = POWER SUPPLEMENT FOR CORPORATE SUSTAINABILITY GOALS

3) A Survey Study on Institutional Influencing Factors

Additionally, we employ structural equation models (SEM) to assess theoretical frameworks explaining relationships among variables affecting HT acceptance, focusing on institutional influencing factors and using data from our representative survey study with $N = 1,000$ participants. Targeting a broad audience, these surveys provide data for statistical analysis and model testing.

III. IMPLICATIONS

The insights gathered from our analyses provide directions for future research in HT acceptance and actionable insights for stakeholders involved in the development and implementation of HTs. Key implications include:

- Validation of Acceptance Measures: Rigorous validation is essential for precise measurement of HT acceptance facets.
- Integration of Participation Variables: Often overlooked in transformative processes, participation variables should be prioritized, focusing on informational contexts and institutional influences.

- Exploration of Societal Narratives and Media Frames: Investigating societal trends and media frames is crucial as they impact technology deployment and uptake.
- Broadening Stakeholder Engagement: Understanding HT acceptance requires exploring acceptance beyond early adopters and the general public, particularly in co-production contexts.
- Focus on Longitudinal Studies: Emphasizing longitudinal studies is crucial to track evolving stakeholder perceptions and continuously adapt strategies.
- Integration of Feedback: Continuously gather and integrate feedback from stakeholders throughout the project.

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