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Autonomous Multi-Factor Energy Flows Controller (AmEFC): Enhancing Renewable Energy Management with Intelligent Control Systems Integration

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Abstract

The transition to sustainable energy systems is one of the defining challenges of our time, necessitating innovations in how we generate, distribute, and manage electrical power. Micro-grids, as localized energy hubs, have emerged as a promising solution to integrate renewable energy sources, ensure energy security, and improve system resilience. The Autonomous multi-factor Energy Flow Controller (AmEFC) introduced in this paper addresses this need by offering a scalable, adaptable, and resilient framework for energy management within an on-grid micro-grid context. The urgency for such a system is predicated on the increasing volatility and unpredictability in energy landscapes, including fluctuating renewable outputs and changing load demands. To tackle these challenges, the AmEFC prototype incorporates a novel hierarchical control structure that leverages Renewable Energy Sources (RES), such as photovoltaic systems, wind turbines, and hydro pumps, alongside a sophisticated Battery Management System (BMS). Its prime objective is to maintain an uninterrupted power supply to critical loads, efficiently balance energy surplus through hydraulic storage, and ensure robust interaction with the main grid. A comprehensive Simulink model is developed to validate the functionality of the AmEFC, simulating real-world conditions and dynamic interactions among the components. The model assesses the system's reliability in consistently powering critical loads and its efficacy in managing surplus energy. The inclusion of advanced predictive algorithms enables the AmEFC to anticipate energy production and consumption trends, integrating weather forecasting and inter-controller communication to optimize energy flow within and across micro-grids. This study's significance lies in its potential to facilitate the seamless incorporation of RES into existing power systems, thus propelling the energy sector towards a more sustainable, autonomous, and resilient future. The results underscore the potential of such a system to revolutionize energy management practices and highlight the importance of smart controller systems in the era of smart grids.

Keywords

Micro-Grid, Smart Grid Interconnection, Hybrid Renewable System, Energy Flow Controller, Battery Management, Hydro Pump, Off-Grid Solutions, Ioniki Autonomous

1. Introduction

The global shift towards renewable energy sources has gained significant momentum in recent years, driven by the pressing need to address climate change, reduce greenhouse gas emissions, and minimize our ecological footprint [1] [2]. Harnessing the power of renewable energy not only offers a cleaner and sustainable alternative to fossil fuel-based energy production but also contributes to the preservation of local ecosystems. As the deployment of renewable energy systems continues to expand [3], there arises a critical need for efficient and intelligent control systems that can optimize energy flows in various applications, to eliminate the uncertainties that arise from "the integration of renewable energy sources" [4].

This academic article aims to explore the role and significance of an autonomous multi-factor energy flow controller in the context of renewable energy micro-grid integration. By leveraging advanced technologies and intelligent algorithms, such a controller can monitor and manage the intricate dynamics of energy supply and demand in real-time, ensuring reliable and optimized operation based mostly on off-grid (without being binding) renewable energy systems.

One of the key challenges in off-grid applications is the limited availability of energy resources. To address this, the autonomous multi-factor energy flow controller integrates multiple factors into its decision-making process. It considers parameters such as energy demand, weather conditions, and the available energy generation capacity. By continuously monitoring and analyzing these factors, the controller can dynamically balance the supply and demand of energy, thus managing energy shortages and optimizing the utilization of available resources, as analyzed in [5]. In exceptional cases, however, the on-grid network may be available.

Pumped Hydro Energy Storage (PHES) stands as a prominent solution for addressing the challenge of efficiently storing excess energy generated by renewable sources during daylight hours and utilizing it during periods of high demand, such as nighttime. This process involves harnessing gravitational potential energy to charge batteries or store energy in the form of elevated water. During off-peak hours when energy demand is low, surplus electricity generated from renewable sources is used to pump water from a lower reservoir to an upper reservoir. This elevation potential energy is then converted back into electricity during peak demand periods by allowing the water to flow downhill through turbines, thereby generating electricity. This unique approach aligns seamlessly with the need to balance energy supply and demand, especially when renewable energy generation is intermittent. Moreover, PHES systems have the capacity to store and discharge large amounts of energy quickly, making them an ideal solution for stabilizing grids, enhancing grid reliability, and providing essential backup power during emergencies. As the integration of renewable energy sources grows, PHES stands out as a robust and proven method for efficiently charging batteries at night, thus ensuring a continuous and reliable energy supply while maximizing the utilization of cleaner energy sources [6].

Intelligent control systems play a pivotal role in the effective management of renewable energy systems [7]. They employ advanced algorithms and predictive models to anticipate energy demand patterns, forecast weather variations, and optimize the operation of energy generation sources, such as solar panels, wind turbines, and micro-hydropower systems. By leveraging real-time data and adaptive control strategies, the autonomous multi-factor energy flow controller ensures the efficient utilization of renewable energy sources, enabling the system to operate autonomously and reliably in remote and challenging environments.

The development of balanced city-scale grids is increasingly becoming a priority in the quest for a sustainable and resilient energy future. A promising approach lies in the integration of micro-grids with intelligent power flow control systems. Micro-grids, as localized energy distribution systems, possess the capacity to generate, store, and manage energy independently. When strategically interconnected within a city, these micro-grids form a robust and decentralized network that can balance energy supply and demand effectively. The key lies in the integration of intelligent control systems that enable real-time monitoring, analysis, and adaptive management of power flows. These systems leverage advanced algorithms to optimize the utilization of various energy sources, including renewable resources, storage systems, and even demand response strategies [8]. By dynamically rerouting power and adjusting energy generation and consumption across interconnected micro-grids, these intelligent control systems ensure an optimized distribution of energy within the city-scale grid. This approach enhances grid stability, minimizes energy losses, and facilitates the integration of cleaner energy sources, consequently contributing to a more sustainable and reliable urban energy landscape.

Furthermore, the integration of remote monitoring and maintenance capabilities enhances the reliability and longevity of off-grid renewable energy systems. Through remote monitoring, operators can access real-time performance data, identify potential issues, and proactively address them, minimizing downtime and optimizing energy generation. This capability becomes particularly crucial in remote or inaccessible areas where regular on-site inspections may be challenging [9].

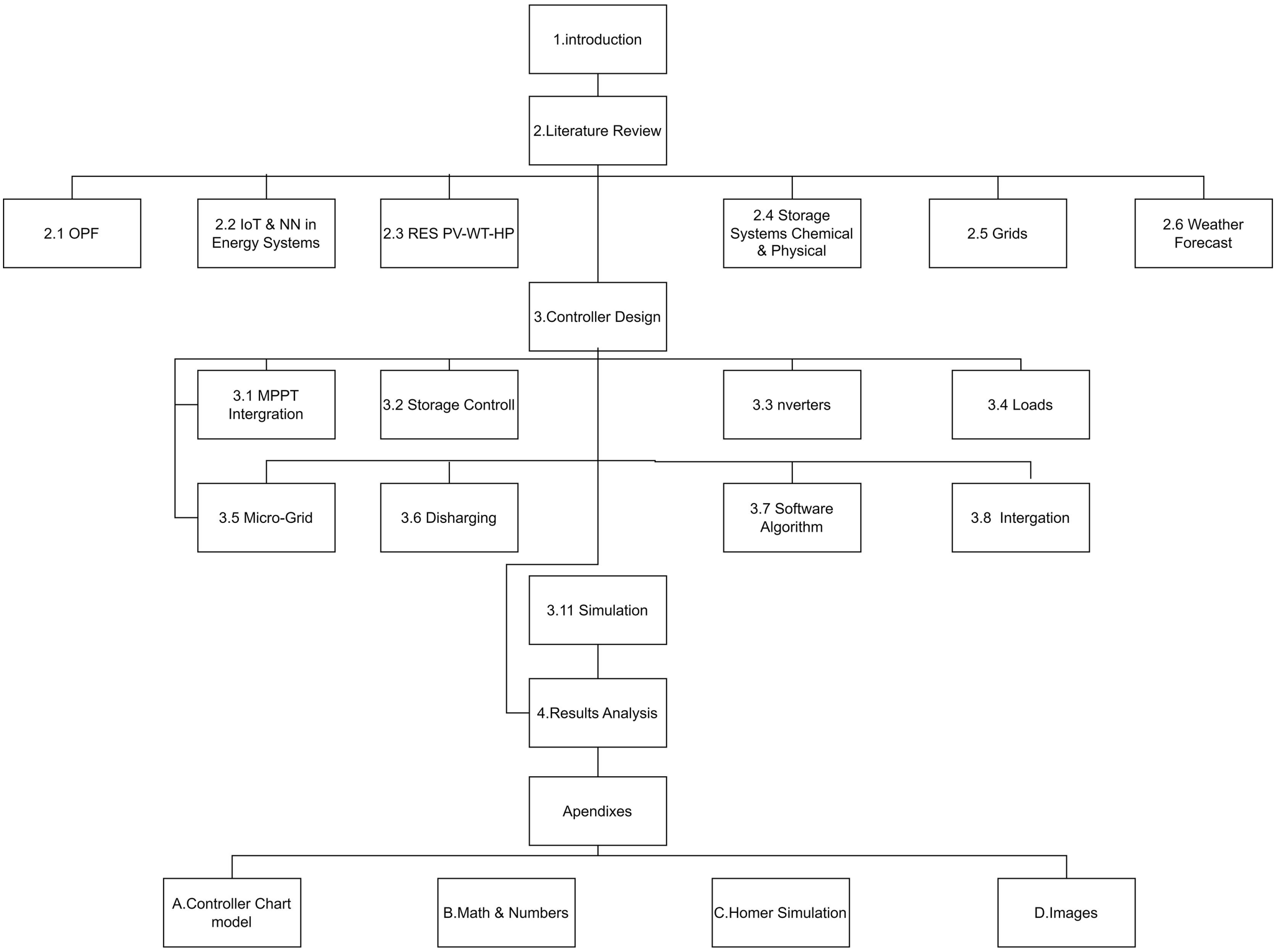
The scope of our work encompasses several key aspects vital for the successful integration of renewable energy systems through intelligent control systems:

1) Reliability and Resilience: Our focus on efficient and intelligent control systems addresses the foundational requirement of ensuring a dependable and resilient energy supply in off-grid scenarios. These systems are designed to meticulously manage energy flows, closely monitor battery storage levels, and employ real-time predictive models for the optimal utilization of available renewable energy resources. Through dynamic adjustments of power generation and consumption, these control systems significantly bolster the reliability and stability of off-grid energy systems, reinforcing their ability to weather uncertainties.

2) Energy Management and Optimization: As off-grid systems often operate with finite energy resources; effective energy management becomes paramount. Our research delves into the application of intelligent control systems that adeptly track energy demand patterns, assess prevailing weather conditions, and gauge the available energy generation capacity. By skillfully balancing the interplay between energy supply and demand, these systems proactively avert energy shortages while optimizing energy utilization. The integration of real-time data and advanced algorithms, as explored in [10], empowers these control systems to harness the full potential of renewable energy sources.

3) Scalability and Flexibility: Another critical facet of our study involves the examination of efficient control systems that facilitate the scalability and adaptability of off-grid energy solutions. These systems exhibit the capability to accommodate variations in energy demand, accommodate system expansions, and seamlessly integrate additional renewable energy sources or storage technologies. By providing this inherent scalability and flexibility, the off-grid systems under consideration can readily adjust to evolving energy requirements. Moreover, in scenarios involving on-grid systems, surplus energy generated can be channeled back into the grid, contributing to a sustainable energy ecosystem. This achievement holds a pivotal role in the development of balanced city-scale grids. It envisions a system where all the AmEFCs (Autonomous Multi-Factor Energy Flows Controllers) of micro-grids will communicate with each other, exchanging real-time information about their local energy demands. This interconnected approach not only optimizes energy distribution but also fosters a seamless exchange of resources, promoting a holistic and sustainable energy network.

We present the structure of this paper in the following diagram.



2. Literature Review

The related work concerns various objects like optimal power flow, IoT, NN, Renewable sources, energy storage, micro-grids and farther scale etc. We process the review in bibliography that concerns the current work.

2.1. Introduction to Traditional and Advanced Solution Methods to OPF (Optimal Power Flow)

The Optimal Power Flow (OPF) problem, first introduced by Carpentier in 1962 [1], is a critical element in power system operations, aiming to balance objectives like minimizing generation costs, reducing power losses, and maximizing social welfare, subject to a variety of constraints including power balance, voltage stability, and generator limits. Despite its long-standing presence in power systems literature, OPF remains a non-linear and non-convex problem, posing substantial challenges to this day [11] [12].

Historically, solution methods for OPF have evolved from traditional techniques, such as Newton's method and linear programming, with pivotal contributions like those by Alsac and Stott [2], to innovative metaheuristic approaches like genetic algorithms and particle swarm optimization. The 1990s marked a significant leap with the introduction of interior point methods, revolutionizing the solution process for large-scale OPF problems [3].

Advances in the 21st century have turned towards convex relaxation techniques, including semidefinite programming (SDP) and second-order cone programming (SOCP), to manage the complexity of OPF, as demonstrated by Lavaei and Low [13], and Gan *et al.* [14]. Furthermore, the integration of stochastic and robust optimization methods has accounted for the uncertainty inherent in renewable energy sources, expanding the scope of OPF under uncertainty [15] [16] [17].

The decentralization trend in power systems has given rise to distributed and decentralized algorithms, tailored for a new era of grid management that encompasses micro-grids and extends to city-wide interconnected systems [18] [19] [20] [21] [22]. Concurrently, machine learning has carved out a role in OPF applications, with researchers leveraging it for solution prediction and system dynamics learning, aiming to streamline the optimization process [23] [24] [25] [26] [27].

In light of these developments, reinforcement learning (RL) has been identified as a promising approach, especially for cooperative multi-agent scenarios in power management, as evidenced in the research outlined in [7]. This approach is particularly relevant for addressing large-scale OPF challenges within extensive networks of interconnected micro-grids, emphasizing the ongoing pursuit of efficient, scalable solutions in the realm of power systems optimization.

2.2. Integration of IoT and Neural Networks in Energy Systems

The integration of IoT and neural networks is significantly impacting the energy sector, promising enhanced management and efficiency [4] [24]. IoT's extensive connectivity combined with the advanced analytics from neural networks opens up new paths for energy optimization, efficient use, and easier adoption of renewable energy sources [28].

The role of IoT in reshaping energy management, as noted by Motlagh *et al.* (2020), spans from supply optimization to improved demand-side efficiency, with cloud computing's real-time data processing supporting this transformation [28]. Concurrently, neural networks like LSTM, as shown by Bouktif *et al.* (2018), offer substantial improvements in predicting electricity demand, assisting utilities in strategic load management and distribution [29].

Merging IoT data with neural network analysis, according to Al-Saadi *et al.* (2023), enhances energy management strategies, particularly those using reinforcement learning, which contributes to more resilient power systems [7]. Moreover, the branch flow model by Farivar and Low (2013) presents an innovative solution to the OPF problem by easing non-convex constraints, thus refining energy system optimization [20].

Overall, the synergy between IoT and neural networks marks a leap toward more efficient and sophisticated energy systems, potentially revolutionizing energy production, distribution, and consumption [28]. This fusion is expected to drive us towards a more sustainable and robust energy infrastructure.

The upcoming section will focus on advancements in renewable energy technologies, including photovoltaic systems, wind turbines, and energy storage mechanisms.

2.3. Renewable Energy Technologies—PV Systems, Wind Turbines, Hydro Pumps

Renewable energy technologies, including PV systems, wind turbines, and hydro pumps, are key to sustainable energy and environmental protection. PV systems are becoming more efficient and cost-effective thanks to advances in material sciences, with significant progress noted by Green *et al.* in perovskite solar cells [30]. Wind turbines have seen improvements in design and maintenance strategies for better energy capture and efficiency, as evidenced in studies by Tchakoua *et al.* [31] and Kusiak *et al.* [32]. Roy and Jadhav have discussed integrating wind energy into power systems, considering the variability of wind [33].

Vertical axis wind turbines (VAWTs) offer a promising alternative to conventional turbines, suitable for urban environments as Kinzel *et al.* have highlighted [34]. Hydro pumps continue to be a reliable energy storage solution, essential for grid stability, and can be effectively integrated with other renewable sources, as shown by Lu *et al.* [35]. Collectively, these innovations in renewable technologies are pivotal for advancing towards a resilient and sustainable energy future.

2.4. Energy Storage Systems—Battery Storage (Chemical)—Water Tower (Physical Dynamics)

Energy storage systems are crucial for harmonizing the intermittency of renewable energy sources with fluctuating power demands, particularly through battery storage and water tower mechanisms.

2.4.1. Battery Storage (Chemical)

Battery storage has become a focal point in energy management due to its high energy density and adaptability, especially with lithium-ion batteries leading the charge in both small-scale and grid applications. These batteries store energy via reversible chemical reactions between their electrodes [36] [37] [38]. Despite recent improvements in battery life and cost-effectiveness, the pursuit for more sustainable and efficient alternatives continues, focusing on new materials and improved chemistries [39] [40] [41].

2.4.2. Water Tower (Physical Dynamics)

Water towers utilize gravitational potential energy for power storage, contrasting the chemical approach of batteries. Energy is stored by pumping water to an elevated reservoir, then released to generate electricity as it flows down. This method offers scalability, environmental friendliness, and long lifecycle benefits [42]-[48].

The benefits of water towers include aiding the integration of renewable energy, stabilizing the grid, time-shifting energy, presenting minimal environmental impact, capitalizing on local resources, providing dependable longevity, and offering emergency power support [49]-[56].

Together, these storage options are critical in the transition towards a more reliable and sustainable energy infrastructure.

2.5. Micro-Grids and City-Scale Grids

Micro-grids represent a decentralized approach to energy systems, capable of operating autonomously or in tandem with the main grid. They integrate diverse distributed energy resources (DERs) and enhance resilience and energy autonomy, maintaining power during main grid outages which is crucial for essential services [57] [58] [59]. Local energy resource optimization is another benefit, as micro-grids can leverage, for example, solar power to minimize carbon footprints in sun-abundant areas [60]. Key to their efficiency is advanced control algorithms managing real-time energy resource dispatch [61].

Scaling up, city-scale grids interlink multiple micro-grids within urban settings, supporting sophisticated energy sharing and management, in alignment with sustainable energy initiatives like the Paris Agreement [58] [62]. These interconnected systems rely on advanced controls and communication for real-time monitoring and predictive analytics, enhancing decision-making for energy allocation, and supporting the integration of electric vehicles as energy storage solutions [63] [64].

2.5.1. Advantages and Challenges

The benefits of these systems are manifold, including improved resilience, renewable energy integration, enhanced efficiency, grid stability, and energy security [65] [66] [67] [68] [69]. However, the implementation faces several hurdles such as regulatory complexities, economic barriers, technical integration challenges, data privacy concerns, and the need for community engagement [70] [71] [72] [73] [74].

2.5.2. Outlook

Future developments in micro-grids [75] and city-scale grids hinge on cost reductions for renewables and advances in storage, demand-side management, and smart grid technologies [76]. Collaborative efforts among various stakeholders are crucial to leverage the full potential of these innovative energy distribution models for a sustainable and resilient energy future [77].

This condensed summary reduces the original text significantly while preserving its essential points and the cited references.

2.6. Photovoltaic and Wind Turbine Energy Production Forecast Using Weather Data

The ability to forecast energy production from photovoltaic (PV) and wind turbine systems is essential for the efficiency and integration of these renewables into power grids. This forecasting largely depends on accurate weather predictions [78] [79] [80]. The use of advanced machine learning techniques, like artificial neural networks, has been effective in creating models that use historical weather data to forecast energy production [81] [82].

The accessibility of weather data from sources like the National Oceanic and Atmospheric Administration (NOAA) and the European Centre for Medium-Range Weather Forecasts (ECMWF) has greatly improved the precision of these forecasts [83] [84]. Real-time data allows for on-the-fly adjustments to the management of energy systems, ensuring more stable grid operation and more effective integration of renewable sources [85].

In summary, leveraging real-time, internet-based weather data for energy production forecasting is key to optimizing renewable energy systems and ensuring their successful incorporation into the energy mix, promising enhanced grid stability and cost efficiency [86].

2.7. Conclusion of Literature Review

We conclude the literature review of the factors that combines the technologies of the AmEFC and renewable energy topics in the following table (**Table 1**).

Within the expansive tapestry of these advancements and potential, the comprehensive review exposes notable lacunae and opportunities that beckon further exploration. The juxtaposition of renewable energy technologies with advanced control systems necessitates incessant inquiry into optimization algorithms, integration modalities, and real-time decision-making frameworks. Furthermore, the pragmatic realization of micro-grids and city-scale grids demands the nuanced negotiation of regulatory intricacies, economic viability conundrums, technical integration complexities, data privacy quandaries, and robust community involvement.

Table 1. Literature review conclusion table.

Subjects			References
OPF			[13] [14]
OPF	+IoT, +NN	+HydroP	[42]
OPF	M. Learning		[5] [7] [15]
OPF	Decentralized		[16] [17] [18]
OPF	Decentralized	Resilient, PS	[19] [20] [21] [22] [23]
IoT	+NN	Energy Sys	[11] [12] [27] [29] [30]
RES Techs	Sustainability		[22] [28] [30] [32] [33] [35]
Storage	Chem Batteries	Water towers	[34] [35] [36] [42]-[48]
Micro Grids	City scale Grids		[57] [58] [59]

Transition to Research's Focus

As we transition from this sweeping literature review, the forthcoming sections of this scholarly discourse will delve into the specifics of our focal research: the formulation and realization of the Autonomous Multi-Factor Energy Flows Controller (AmEFC), aimed at optimizing the assimilation of renewable energy and streamlining energy management within the milieu of micro-grids and city-scale grids. Envisioned as an extension of the bedrock established by the corpus of reviewed literature, our research seeks to contribute substantively to the cultivation of intelligent and resource-efficient energy systems poised to circumvent the challenges intrinsic to contemporary energy landscapes.

3. AmEFC Design and Architecture Framework

The prototype micro-grid, designed for the application of AmEFC, comprises a synergistic assembly of cutting-edge renewable energy technologies, each offering its unique benefits to bolster efficiency, resilience, and sustainability.

Photovoltaic Solar (PV) Systems: At the forefront are the advanced PV systems, which have been beneficiaries of rapid strides in materials science and engineering. A pivotal contribution to this domain is the exploration by Green *et al.* (2019) into perovskite solar cells [30]. Their research unveiled an avenue for potential enhancements in PV efficiency, underscoring the transformative potential of innovative materials in solar technology. The design philosophy emphasizes modularity, allowing for the system's scalability and catering to varying energy requirements.

Vertical Axis Wind Turbine (VAWT): The micro-grid incorporates VAWTs, prized for their multifaceted advantages. Their design ensures lower auditory disturbances, while ground-level accessibility streamlines maintenance tasks. Furthermore, these turbines demonstrate heightened efficacy under turbulent wind conditions, harnessing energy even when conventional turbines might falter. The VAWT configuration is also envisioned to be modular, facilitating future expansions as necessary.

Hydro Pumps: Augmenting the energy storage capabilities of the micro-grid are hydro pumps. By exploiting gravitational potential energy, they present a reliable avenue to squirrel away power for later use. Their inclusion ensures a steady energy source, adept at buttressing grid stability and addressing sporadic energy demands. Significantly, Lu *et al.*'s study in 2018 elucidates the complementary relationship between hydro-pumped storage and other renewable like wind and solar [35]. This symbiosis underscores the viability of a micro-grid that seamlessly weaves various energy sources into a cohesive unit. Much like its peers, the hydro pump system is designed for scalability, anticipating future growth and diversification.

3.1. MPPT Integration with the Prototype Micro-Grid for AmEFC Application

Building upon the innovative framework of the prototype micro-grid, an integral component warrants special mention—the Maximum Power Point Trackers (MPPTs). Designed to optimize the extraction of energy from each Renewable Energy Source (RES), every RES within the micro-grid, be it the PV system, VAWT, or hydro pumps, will be individually interfaced with its dedicated MPPT. This ensures that each energy source operates at its peak performance, maximizing efficiency and energy harvest.

The interconnection of these MPPTs culminates at the DC Bus, serving as a unified hub for energy distribution and management. This architecture not only ensures streamlined power flow but also provides a modular approach, allowing for easy scalability and potential integration of additional RES in the future.

Beyond the realm of energy optimization, the MPPTs play a pivotal role in data management and communication. They are intricately networked to facilitate real-time data sharing among themselves. This data-centric approach allows for instantaneous upload of energy production metrics to the cloud infrastructure of the MPPT manufacturer. This real-time data integration offers a multitude of benefits, from remote monitoring to predictive analytics, ensuring that the AmEFC application is not just about harnessing energy but also about harnessing the power of data to drive informed decisions and optimizations. The block diagrams are presented in (**Figure 1** & **Figure 2**).

3.2. Incorporation of Battery Strings in the Prototype Micro-Grid for AmEFC Application

Further bolstering the robustness of the prototype micro-grid is the strategic integration of battery strings. Recognizing the variable nature of energy production from renewable sources, the inclusion of batteries is pivotal to ensure consistent power availability and optimized energy utilization. The micro-grid facilitates flexibility in battery technology choice, accommodating either Lead-Acid or advanced Lithium-based battery systems, catering to specific requirements and considerations of the deployment scenario.

Each battery string is equipped with a state-of-the-art Battery Management System (BMS). The BMS plays a quintessential role in safeguarding battery health and longevity. It meticulously monitors and manages critical parameters like voltage, current, and temperature. Its algorithms are designed to precisely control the charging and discharging phases, ensuring that the batteries are neither overcharged nor excessively depleted, thereby preserving their lifespan and operational efficiency.

Beyond its primary role of battery health and charge management, the BMS serves as a nexus for data acquisition and communication. Similar to the MPPTs, the BMS systems are endowed with the capability to relay real-time data on battery performance and health metrics to the cloud platform of the battery manufacturer. This data-centric integration paves the way for remote monitoring, health diagnostics, and prognostic analytics, granting stakeholders invaluable insights into the performance and expected lifespan of the battery assets.

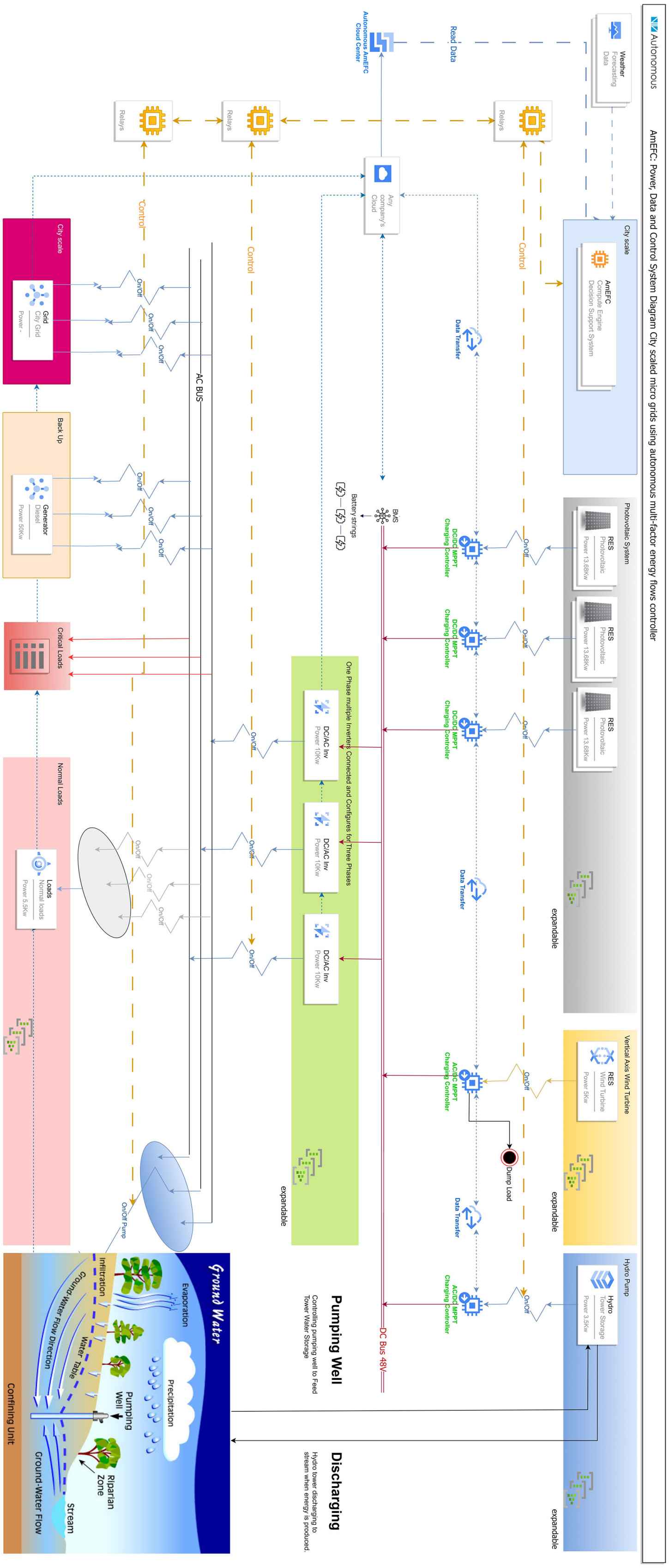
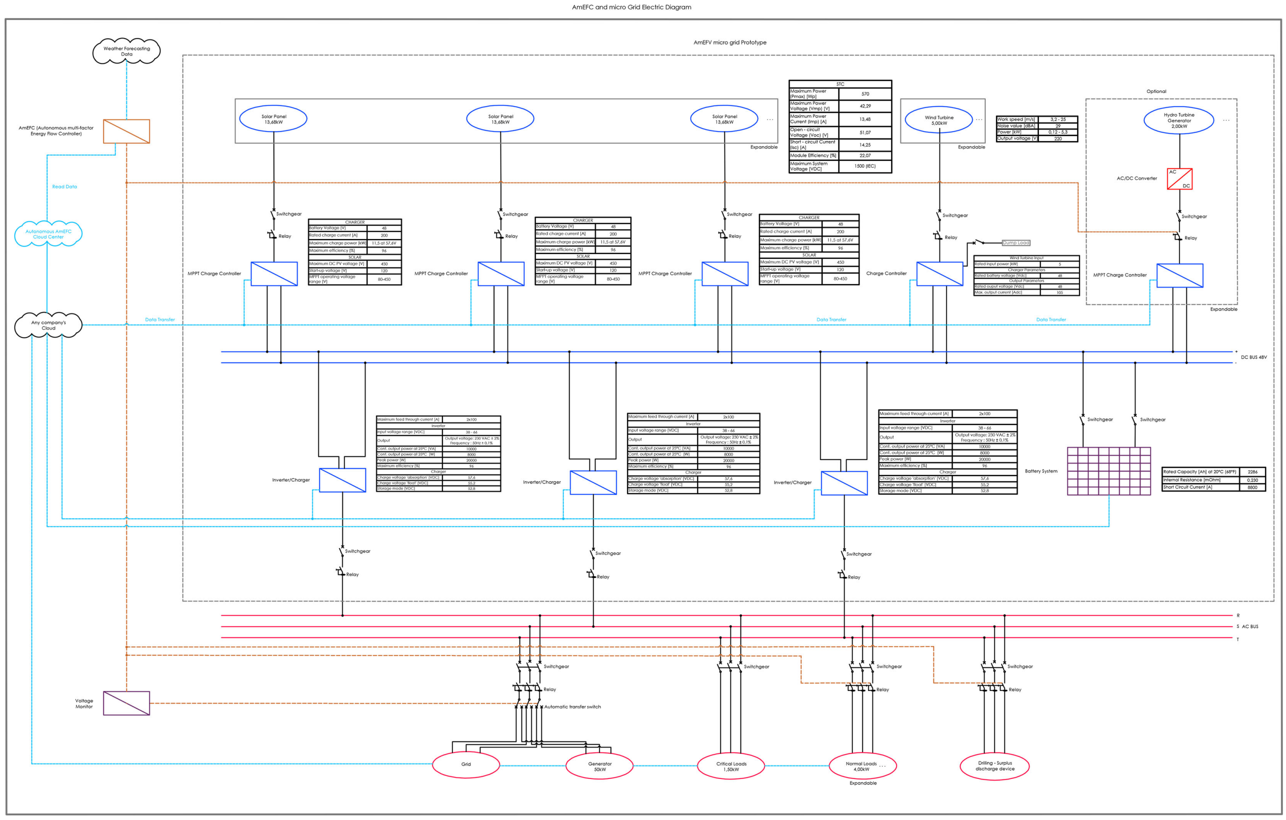


Figure 1. AmEFC & prototype micro-grid block diagram full design.



STC	
Maximum Power (Pmax) [Wp]	570
Maximum Power Voltage (Vmp) [V]	42,29
Maximum Power Current (Imp) [A]	13,48
Open - circuit Voltage (Voc) [V]	51,07
Short - circuit Current (Isc) [A]	14,25
Module Efficiency [%]	22,07
Maximum System Voltage [VDC]	1500 (IEC)

Work speed [m/s]	3,2 - 25
Noise value [dBA]	29
Power [kW]	0,12 - 5,3
Output voltage [V]	220

CHARGER	
Battery Voltage [V]	48
Rated charge current [A]	200
Maximum charge power [kW]	11,5 at 57,6V
Maximum efficiency [%]	96
SOLAR	
Maximum DC PV voltage [V]	450
Start-up voltage [V]	120
MPPT operating voltage range [V]	80-450

CHARGER	
Battery Voltage [V]	48
Rated charge current [A]	200
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Maximum charge power [kW]	11,5 at 57,6V
Maximum efficiency [%]	96
SOLAR	
Maximum DC PV voltage [V]	450
Start-up voltage [V]	120
MPPT operating voltage range [V]	80-450

Wind Turbine Input	
Rated input power [kW]	5
Charger Parameters	
Rated battery voltage [Vdc]	48
Output Parameters	
Rated ouput voltage [Vdc]	48
Max. output current [Adc]	105

Maximum feed through current [A]	2x100
Inverter	
Input voltage range [VDC]	38 - 66
Output	Output voltage: 230 VAC ± 2% Frequency : 50Hz ± 0,1%
Cont. output power at 25°C [VA]	10000
Cont. output power at 25°C [W]	8000
Peak power [W]	20000
Maximum efficiency [%]	96
Charger	
Charge voltage 'absorption' [VDC]	57,6
Charge voltage 'float' [VDC]	55,2
Storage mode [VDC]	52,8

Maximum feed through current [A]	2x100
Inverter	
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Cont. output power at 25°C [W]	8000
Peak power [W]	20000
Maximum efficiency [%]	96
Charger	
Charge voltage 'absorption' [VDC]	57,6
Charge voltage 'float' [VDC]	55,2
Storage mode [VDC]	52,8

Rated Capacity [Ah] at 20°C (68°F)	2286
Internal Resistance [mOhm]	0,230
Short Circuit Current [A]	8800

Figure 2. AmEFC & prototype micro-grid electric diagram.

In summation, the inclusion of battery strings, whether Lead-Acid or Lithium-tech, extends the functional horizon of the AmEFC prototype micro-grid. Not only do they act as energy reservoirs, buffering against the intermittencies of renewable sources, but with the integrated BMS, they also usher in an era of smart energy storage, where decisions are not just based on real-time needs but are informed by a wealth of data, ensuring optimal operation and sustainability of the energy infrastructure.

3.3. Integration of Single-Phase Inverters to the Prototype Micro-Grid for AmEFC Application

In the pursuit of flexibility and adaptability within the prototype micro-grid, a novel approach in inverter technology has been employed. Specifically, instead of a traditional three-phase inverter, the design leverages three single-phase inverters, seamlessly interlinked to serve as a unified three-phase system. This arrangement provides not only a pathway for energy conversion from DC sources like PVs, wind turbines, and battery strings to AC loads but also guarantees an inherent redundancy and modularity to the system.

The strategic advantage of utilizing three single-phase inverters becomes apparent when considering the scalability of the prototype. Should the load consumption demands vary or expand in the future, the micro-grid's architecture easily allows for the integration of additional single-phase inverters. This modularity ensures that the micro-grid can be dynamically tailored to meet evolving energy needs without necessitating a complete overhaul of the core infrastructure.

Each of the inverters is imbued with smart connectivity features, echoing the overarching theme of data-centric operation observed in the other components of the micro-grid. These inverters are not just passive components; they are equipped with sensors and communication modules that continuously monitor energy flows. This data is uploaded in real-time to the cloud platform maintained by the inverter's manufacturer. Such cloud integration facilitates remote monitoring, analytics, and potential predictive maintenance, minimizing downtime and ensuring consistent energy delivery.

Moreover, the inverters are interconnected, establishing an intra-grid communication network. This inter-inverter communication is instrumental in coordinating their operations, maintaining phase synchronization, and ensuring a balanced load distribution across the three-phase system.

3.4. Load Classification and Management in the Prototype Micro-Grid for AmEFC Application

Within the sophisticated architecture of the AmEFC prototype micro-grid, energy consumption is intelligently stratified according to the significance and priority of the connected loads. This hierarchical structure is particularly crucial to ensure a seamless balance between energy production, storage, and consumption, thereby providing consistent and uninterrupted power supply to essential services.

Critical Loads: These represent the cornerstone of the system's commitment to reliability. Critical loads encompass essential equipment and infrastructure that demand an unwavering 24/7 energy supply. Such loads might include, but are not limited to, life-support systems in healthcare settings, emergency lighting, communication systems, and other indispensable services. The micro-grid's energy forecasting algorithms are geared towards ensuring that the combination of renewable energy production and battery storage will always suffice to meet the energy requirements of these critical loads, come what may.

Normal Loads: Constituting the bulk of daily energy consumption, normal loads represent everyday electrical appliances and systems, ranging from lighting and HVAC to household appliances. While these loads also benefit from the 24/7 power supply, they are subject to a hierarchy of services. In situations where energy production lags or unforeseen consumption spikes occur, the micro-grid prioritizes the critical loads, potentially drawing from the city-scale grid to ensure that normal loads remain operational without affecting the critical ones.

Surplus Energy Hydro Pump Load: Serving as a tangible manifestation of energy surplus management, the hydro pump load introduces a unique dimension to the micro-grid. In scenarios where the energy production significantly overshadows consumption, instead of letting this surplus dissipate, the system funnels it towards powering hydro pumps. These pumps transfer drilled water to elevated storage towers, effectively converting surplus electrical energy into gravitational potential energy. However, this operation isn't executed blindly. The micro-grid, equipped with weather forecasting data and real-time battery charge levels, intelligently decides if it's optimal to divert this surplus to the hydro pump.

3.5. Grid-Connected Support and Auxiliary Power Sources for AmEFC Micro-Grid

To further bolster the resilience and reliability of the AmEFC micro-grid, two additional layers of energy support are seamlessly integrated: the grid-connected support and an auxiliary diesel/electric generator. Both of these are introduced as contingencies, ensuring that the micro-grid remains impervious to energy lags and unforeseen consumption spikes, making the system not only versatile but also exceptionally energy-secure.

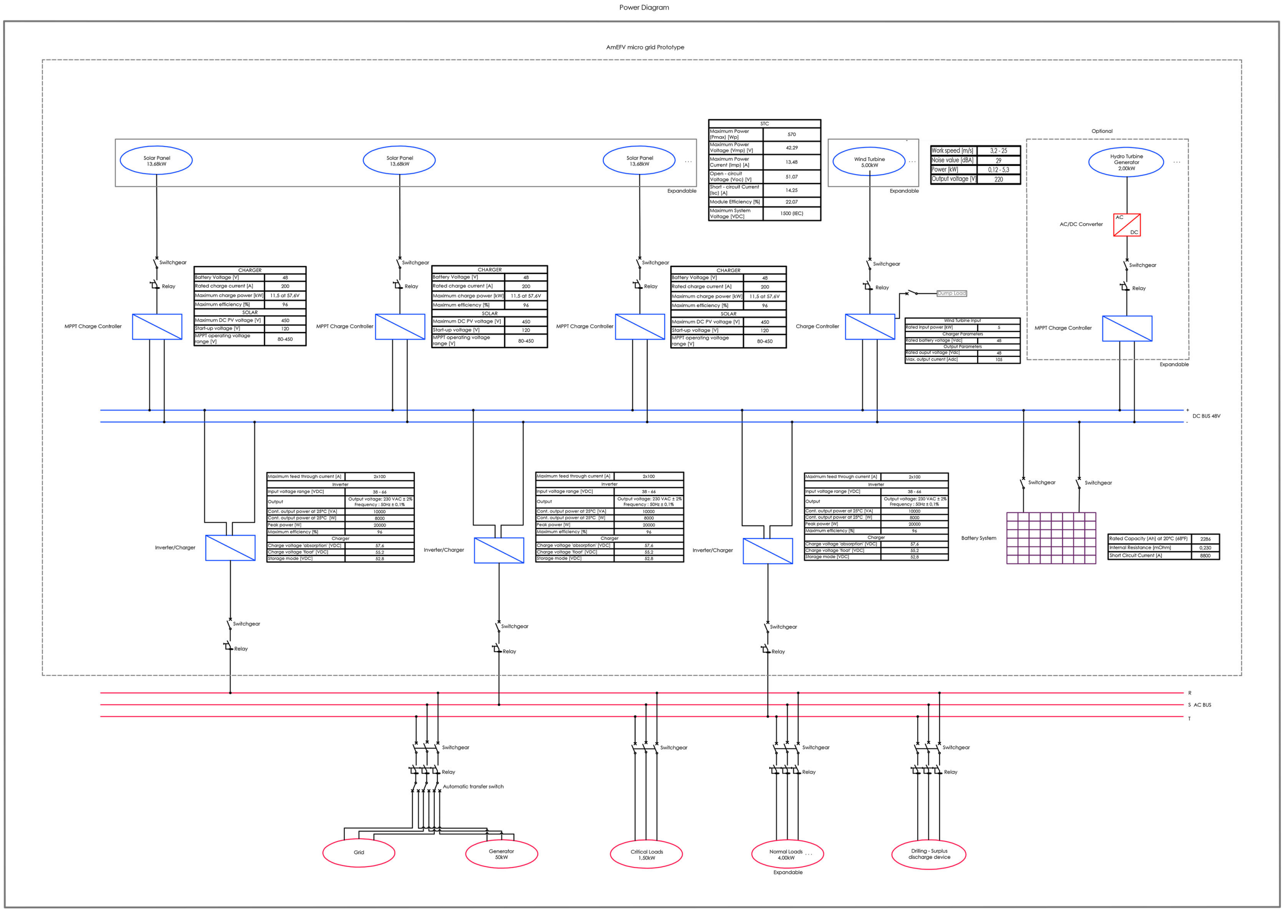
On Grid-Connected Support: The micro-grid is designed to seamlessly interface with the city-scale grid, serving as an external reservoir of energy when needed. This grid-connected support comes into play especially during prolonged periods of low renewable energy production or during unexpected surges in demand. By drawing power from the larger grid, the system ensures that its internal energy balance remains undisturbed, preserving the sanctity of its critical and normal loads. Moreover, this connection also offers the micro-grid an opportunity to feed surplus energy back into the grid during periods of excess production, fostering a symbiotic relationship that benefits both the local and broader energy ecosystems.

Diesel/Electric Generator: While the grid-connected support offers a robust backup, there might be situations or locations where the city-scale grid itself is compromised, such as during widespread power outages or in remote areas. For such scenarios, the AmEFC micro-grid is equipped with the option to integrate a diesel/electric generator. This auxiliary power source can be swiftly activated to bridge any energy gaps, ensuring that the micro-grid remains operational and continues to power its loads without interruption. Designed for efficiency and minimal environmental impact, these generators serve as the last line of defense, underlining the system's commitment to uninterrupted power supply no matter the external circumstances.

All the above-mentioned devices and their interconnections are presented in (**Figure 3**) including break circuits and relays.

3.6. New Possible Discharging Capabilities in Prototype AmEFC Micro-Grid

Within the paradigm of integrated energy systems, the adept management of superfluous generation is paramount. In configurations inclusive of wind turbines, it's conceivable to encounter scenarios where wind-driven power generation surpasses the system's consumption and storage capacity. This phenomenon



STC	
Maximum Power (Pmax) [Wp]	570
Maximum Power Voltage (Vmp) [V]	42,29
Maximum Power Current (Imp) [A]	13,48
Open - circuit Voltage (Voc) [V]	51,07
Short - circuit Current (Isc) [A]	14,25
Module Efficiency [%]	22,07
Maximum System Voltage [VDC]	1500 (IEC)

CHARGER	
Battery Voltage [V]	48
Rated charge current [A]	200
Maximum charge power [kW]	11,5 at 57,6V
Maximum efficiency [%]	96
SOLAR	
Maximum DC PV voltage [V]	450
Start-up voltage [V]	120
MPPT operating voltage range [V]	80-450

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MPPT operating voltage range [V]	80-450

Work speed [m/s]	3,2 - 25
Noise value [dBA]	29
Power [kW]	0,12 - 5,3
Output voltage [V]	220

Wind Turbine Input	
Rated input power [kW]	5
Charger Parameters	
Rated battery voltage [Vdc]	48
Output Parameters	
Rated ouput voltage [Vdc]	48
Max. output current [Adc]	105

Maximum feed through current [A]	2x100
Inverter	
Input voltage range [VDC]	38 - 66
Output	Output voltage: 230 VAC ± 2% Frequency : 50Hz ± 0,1%
Cont. output power at 25°C [VA]	10000
Cont. output power at 25°C [W]	8000
Peak power [W]	20000
Maximum efficiency [%]	96
Charger	
Charge voltage 'absorption' [VDC]	57,6
Charge voltage 'float' [VDC]	55,2
Storage mode [VDC]	52,8

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Storage mode [VDC]	52,8

Rated Capacity [Ah] at 20°C (68°F)	2286
Internal Resistance [mOhm]	0,230
Short Circuit Current [A]	8800

Figure 3. AmEFC & prototype micro-grid Electric Diagram.

is especially accentuated when the affiliated battery storage units are saturated. Historically, conventional methods would either disconnect the wind turbine or redirect the surplus energy to a dump load, serving as a preventive measure against potential system overloads. Contrastingly, the prototype AmEFC micro-grid presents a pioneering resolution to this conundrum. During intervals of energy overproduction, the excess power actuates hydro pumps, thereby facilitating the transfer of water into a designated tower. This strategic operation not only capitalizes on the superabundant energy but also primes the system for impending energy demands, transforming the stored water into a potential energy reservoir. In the eventuality of the water tower reaching its volumetric threshold, the AmEFC micro-grid is ingeniously devised to channel the overflow into an adjacent stream. This ensures a consistent equilibrium within the energy infrastructure, while concurrently optimizing resource utilization and averting wastage. This avant-garde mechanism accentuates the prototype AmEFC micro-grid's commitment to ensuring resourceful and sustainable energy management.

3.7. AmEFC Software: The Nerve Center of the Micro-Grid System

The sophistication of the AmEFC micro-grid doesn't solely lie in its physical components. At the heart of this complex network of energy generators, storage systems, and diverse load categories is the AmEFC software, a cutting-edge computational and control framework designed to seamlessly harmonize the intricate dance of energy flows throughout the system.

Cloud-Connected Equipment Data Streams: Virtually every component of the micro-grid—from the MPPTs, inverters, charging controllers, to the BMS—not only performs its designated function but also continually communicates vital real-time operational data to their respective producer clouds. This constant stream of information provides an instantaneous snapshot of the micro-grid's health, performance, and potential areas of optimization.

Data Aggregation and Storage: The AmEFC software goes a step beyond by collating this ocean of data into its centralized cloud database. Here, the information is systematically organized and stored, encompassing everything from water tower level heights, consumption histories of critical and normal loads, energy surplus records, to intricate weather forecasting data. This centralized repository ensures that any decision made by the system is rooted in comprehensive, up-to-the-minute information.

Advanced Computational Strategies: Armed with this holistic view, the AmEFC software employs state-of-the-art computational methodologies to drive its decision-making processes. Using Optimal Power Flow (OPF) strategies, it determines the most efficient distribution of energy across the grid, ensuring that each component operates at its peak potential while meeting the demands of the connected loads.

Reinforcement Learning (RL)-based Control: Going beyond traditional algorithmic solutions, the AmEFC software incorporates RL-based solutions into its arsenal. By learning from historical data, recognizing patterns, and adapting to new situations, the RL mechanisms can make predictive and proactive decisions. For instance, based on weather forecasting data and past consumption trends, the system might optimize the energy stored in batteries in anticipation of a cloudy day, ensuring uninterrupted power supply to critical loads.

Real-time Decisions and Automated Control: The combination of OPF and RL ensures that the AmEFC software isn't just reactive but also proactive. Whether it's diverting surplus energy to the hydro pump, drawing power from the grid during peak demand, or optimizing the battery charging cycles based on weather forecasts, the system continually makes real-time decisions to maintain optimal energy flow and system efficiency (**Figure 4**) applying to connection diagram (**Figure 5**).

3.8. The Execution Backbone: AmEFC Controller's Hardware and Software Integration

The true brilliance of the AmEFC system becomes apparent when examining the execution mechanism underpinning the entire micro-grid's operation—the AmEFC Controller. The synergy between its software computations and hardware interfacing guarantees seamless energy flow, ensuring optimal system performance and reliability.

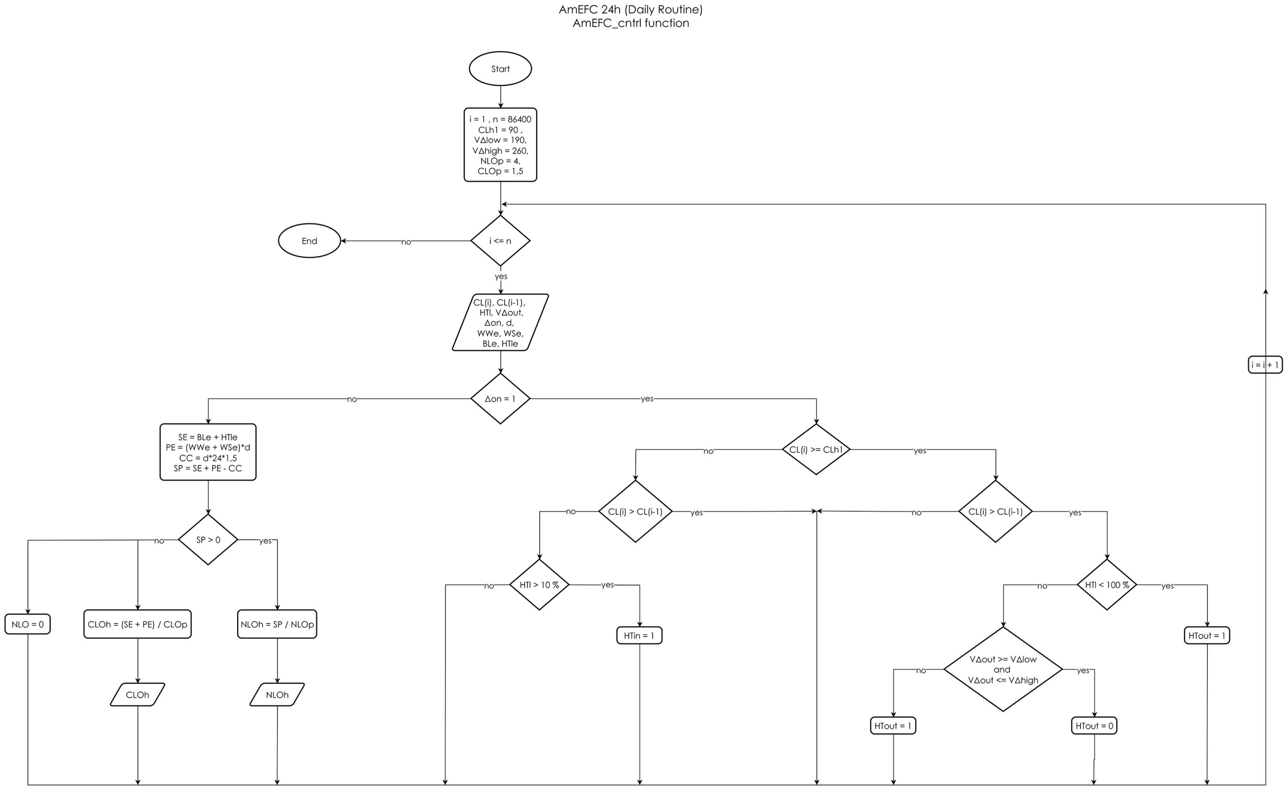


Figure 4. Controller's flowchart (*Refer to appendix A for pseudo code and variables definition).

Hardware Interfacing: At the core of the AmEFC Controller's execution is its comprehensive electrical connectivity to the micro-grid's vast array of devices and load power inputs. This connectivity is facilitated through a meticulously organized array of relays. These relays serve as the tactile interface, allowing the Controller to physically orchestrate the energy distribution across the micro-grid by establishing or severing connections as needed.

Client-side Software Operations: While the AmEFC Cloud Center serves as the data repository and computational nerve center for all interconnected micro-grids, the on-site (client-side) AmEFC software plays a crucial role in real-time operations. Tailored specifically for the individual nuances and requirements of its designated micro-grid, this software continuously fetches pertinent data from the AmEFC Cloud Center. With access to both real-time and historical data, the software is equipped to make informed, timely decisions about energy allocation and flow.

Dynamic Energy Flow Control: Based on the computations derived from the cloud data, the client-side software dynamically manages energy flows throughout the micro-grid. By manipulating the connected relays, it can swiftly connect or disconnect various components, enabling a fluid response to change energy demands or supply fluctuations. This adaptive approach ensures that the micro-grid consistently operates at peak efficiency, regardless of external variables.

AmEFC Controller: A Holistic Solution: The AmEFC Controller's true prowess is its harmonious integration of software and hardware components. While

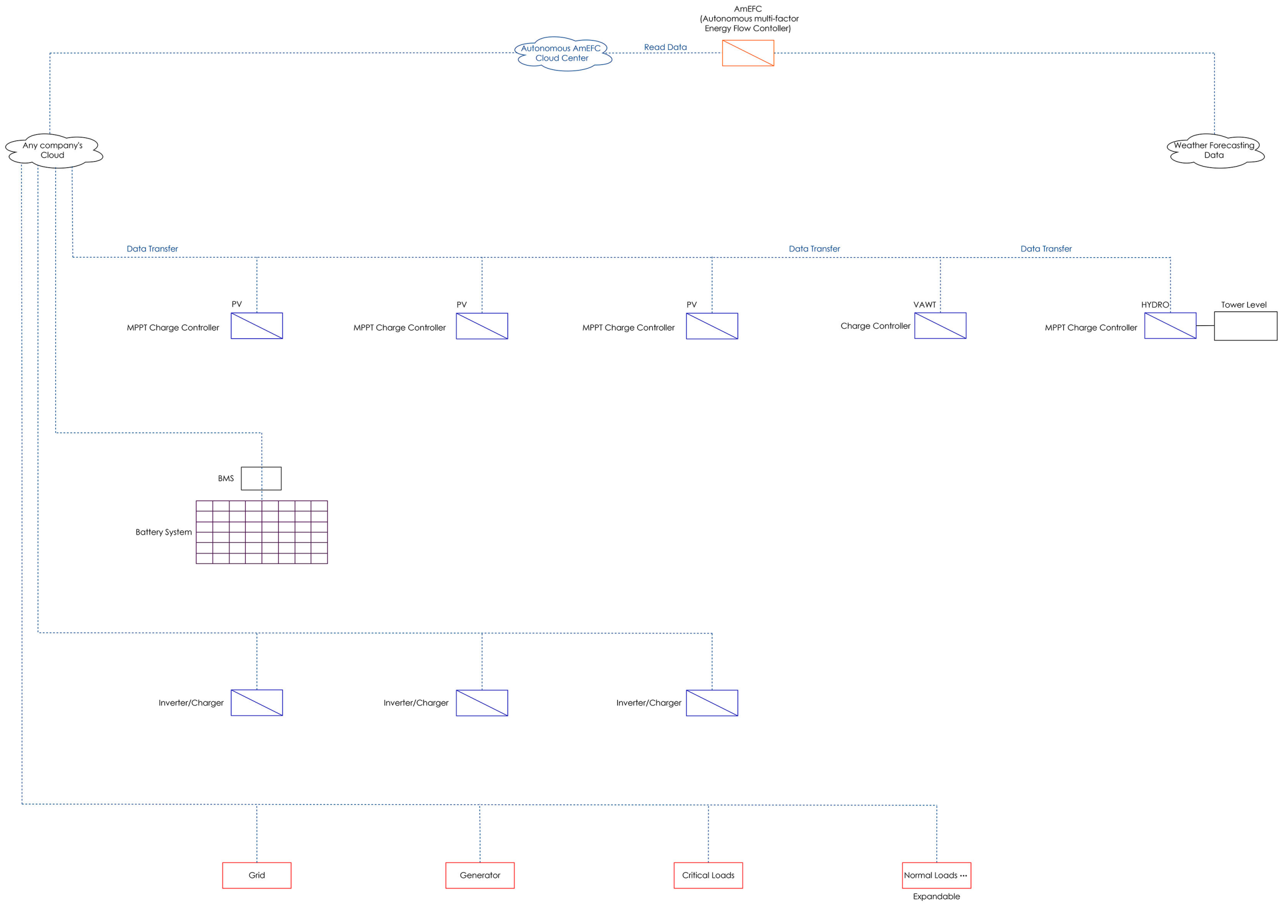


Figure 5. AmEFC (Hardware & Software) connection data diagram.

the software, with its sophisticated computational capabilities, dictates the energy management strategy, the hardware acts on these directives in real-time through the relay system. Together, they form a cohesive unit, ensuring the micro-grid is not just smart but also responsive and adaptable.

All the connections of the AmEFC and the micro-grid devices are presented in (**Figure 6**).

3.9. Architectural Framework Summarized of AmEFC (Autonomous Multi-Factor Energy Flow Controller)

To ensure that the AmEFC embodies principles of scalability, adaptability, and resilience, the architectural framework is structured across different levels. These hierarchical levels form a tiered approach, providing a systematic layout to the energy control ecosystem.

3.9.1. Level 1: Core Energy Generation & Storage Components

Renewable Energy Sources (RES): Includes advanced Photovoltaic Solar (PVS) systems, Vertical Axis Wind Turbines (VAWT), and Hydro Pumps. Their modular nature allows for scalability based on evolving energy demands.

Maximum Power Point Trackers (MPPTs): Essential for optimal energy extraction from RES. Interconnected to upload real-time data to the producer's centralized cloud.

Battery Storage System: Available in Lead-Acid or Lithium technology variants, they are crucial for energy storage and management, with the BMS controlling and monitoring their operations.

DC/AC Inverters: Three single-phase inverters can be merged to emulate a three-phase system, ensuring adaptability to different load requirements.

3.9.2. Level 2: Dynamic Load Management

Critical Loads: Imperative appliances and services demanding uninterrupted power.

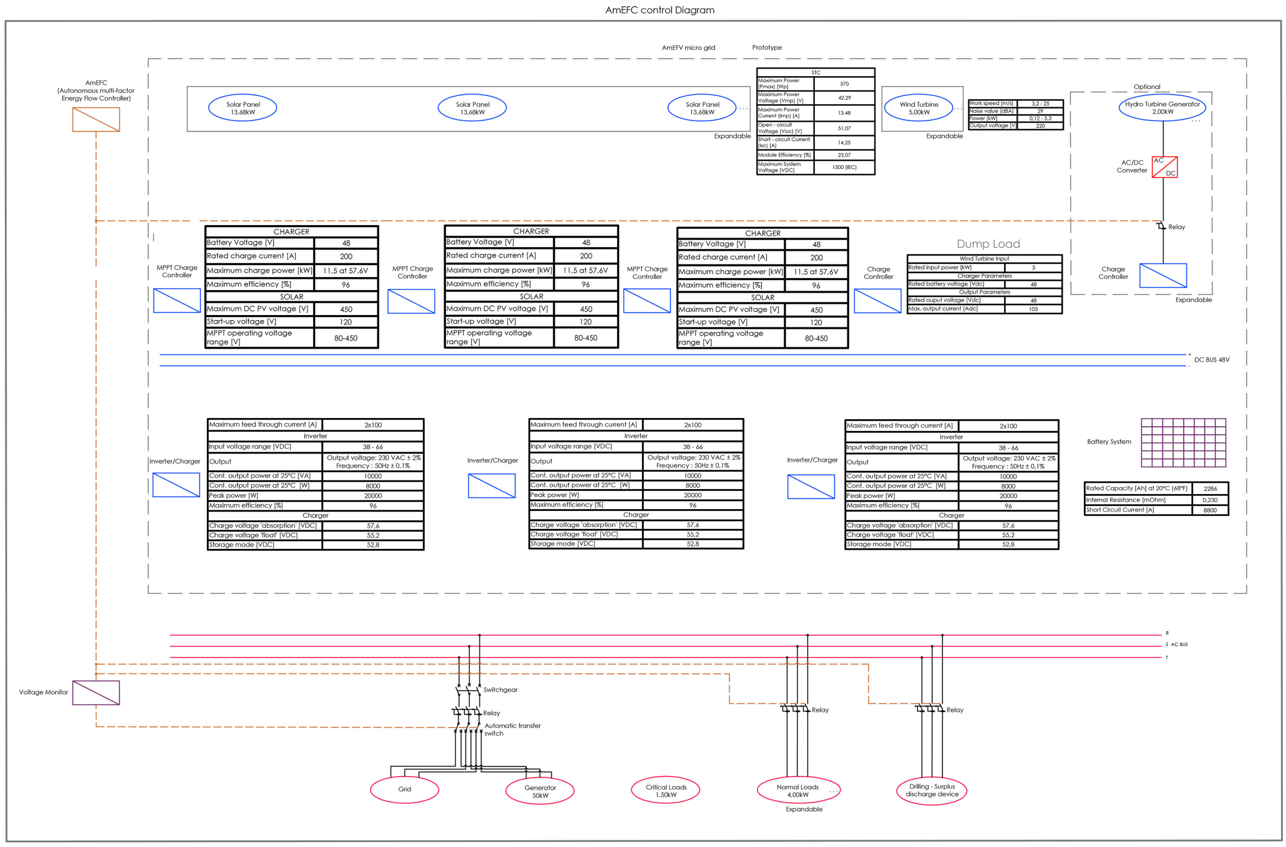
Normal Loads: Regular devices and systems which can be powered continuously, adjusting energy sourcing strategies as per availability.

Surplus Energy Hydro Pump Load: A dynamic energy storage unit, adaptable to energy surplus situations and subject to factors like weather forecasts and battery charge conditions.

3.9.3. Level 3: Supplemental Energy & Backup Mechanisms

City-Scale Grid Connectivity: Facilitates adaptability by drawing power from the city grid during low energy generation intervals.

Diesel/Electric Generator: Ensures resilience by standing as a backup power source during prolonged energy shortages.



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Internal Resistance [mOhm]	0,230
Short Circuit Current [A]	8800

Figure 6. AmEFC & prototype micro-grid control diagram.

3.9.4. Level 4: The Centralized AmEFC Controller & Decision Systems

Data Integration & Cloud Center: The AmEFC Cloud Center acts as a data reservoir, collecting insights from various components, setting the stage for data-driven decision making.

Execution Backbone: The relay network, controlled by the AmEFC software, transforms data insights into actionable energy flow decisions, thereby demonstrating the system's adaptability and resilience.

3.9.5. Level 5: New Possible Discharging Capabilities in Prototype AmEFC Micro-Grid

Dynamic Discharge Management: In situations where there's excessive wind energy, and batteries are at peak capacity, the system disconnects the wind turbine, rerouting the excess power to dump loads. In the hybrid model, the hydro pump directs water to the tower for storage. If the tower reaches its full capacity, the excess water can be safely discharged into a stream, offering an innovative mechanism to manage surges in energy production.

Through this multi-level architecture, the AmEFC showcases a balance between foundational energy components and advanced decision-making systems. The layered approach ensures that while the base remains robust and scalable, the top layers are nimble and adaptable, ensuring a resilient energy framework for the future.

3.10. Interconnectivity Challenges and Opportunities of AmEFC in City-Scale Micro-Grids

In the evolving energy landscape, the challenge of integrating multiple AmEFCs across diverse micro-grids via the AmEFC Cloud Center presents both complexities and unprecedented opportunities. At the heart of this ecosystem, the AmEFC Cloud Center becomes the nexus, mediating energy exchanges, predictive analytics, and real-time adaptability, transcending traditional grid constraints.

One core challenge lies in synchronizing myriad micro-grids with varying generation capacities, consumption patterns, and operational contingencies. Diverse geographic locations introduce variability in energy generation, especially with renewable sources that are highly dependent on environmental factors. This discrepancy can lead to instances where one micro-grid experiences an energy surplus while another faces a deficit.

However, this challenge births an opportunity through the capabilities of the AmEFC local controllers. By being seamlessly interconnected and pooling their data into the central Cloud Center, these controllers enable real-time energy flow decisions not just at a micro-level but also at the macro, city-scale level. For instance, should a particular micro-grid register an energy surplus, and forecasting data indicates a period of full generation ahead due to weather conditions, the AmEFC local controller can dynamically decide the energy flow strategy. Instead of conventionally feeding its surplus to local energy storage like the water tower, it can channel this excess to the city grid. This energy injection comes with a contractual understanding, facilitated by the Cloud Center, where the supplying micro-grid can retrieve equivalent energy from the city grid in times of need, essentially acting as a short-term energy loan. Such a give-and-take mechanism, governed by the AmEFC controllers, not only optimizes local energy distribution but also fortifies the broader city grid, enhancing resilience, adaptability, and sustainability.

3.11. AmEFC Controller & Micro-Grid Simulation

The Simulink model (Figure 7) represents the comprehensive functionality of the on-grid AmEFC micro-grid prototype. Designed to holistically integrate Renewable Energy Sources (RES), such as PV systems, Wind Turbines, and Hydro Pumps, with a Battery Storage System equipped with a BMS (Battery Management System), its main objective is to manage and streamline energy distribution across different load categories. A pivotal emphasis of the model is to consistently maintain power to critical loads, while also ensuring seamless interaction with the main grid.

3.11.1. Description of the On-Grid AmEFC Micro-Grid Prototype Simulink Model

Components:

PV Systems: This module (Figure 8) simulates energy production from solar panels (3 X PV 13.6 kW Array), taking into account specific irradiation from Appendix B, math and numbers, and temperature parameters.

The system illustrates PWM generator. A simplified model of an IGBT/ Diode is used. The converters are controlled in open loop with the PWM Generator blocks. The Voltage of DC Bus is stabilized on 48 V.

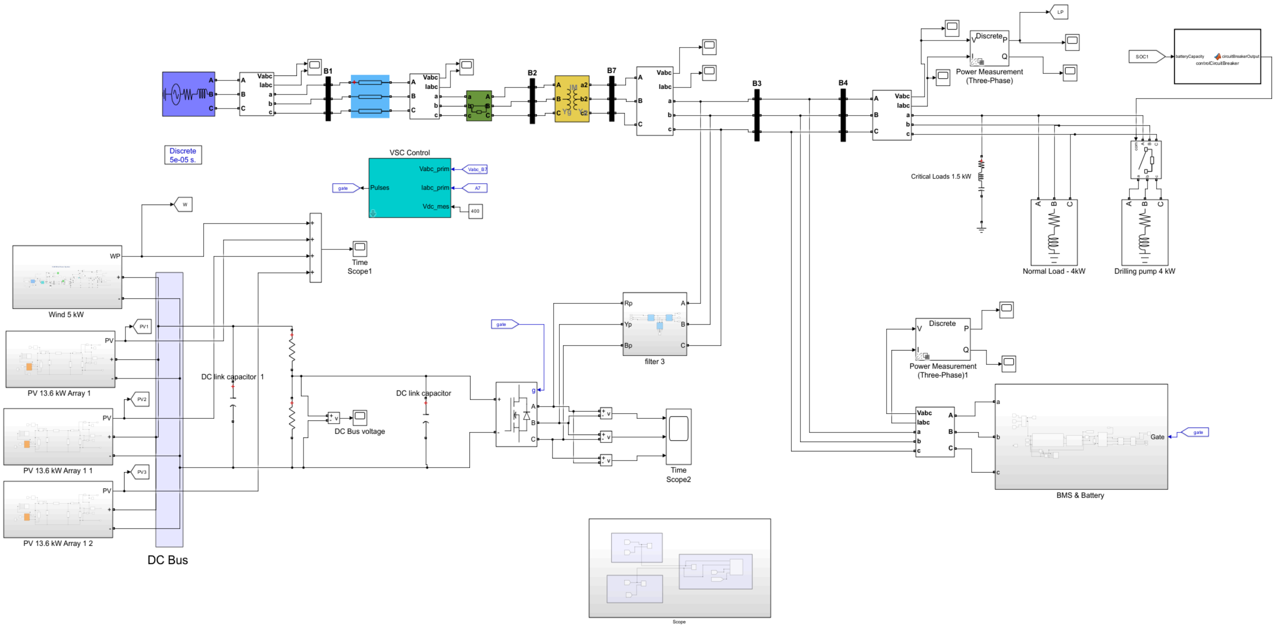


Figure 7. The model in Simulink.

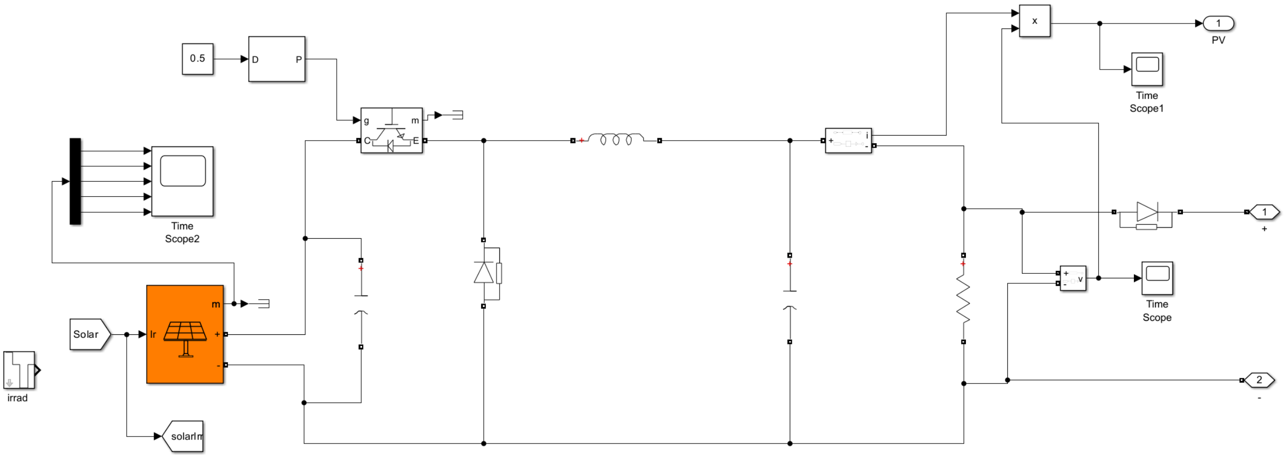


Figure 8. PV System Diagram on Simulink.

In order to allow further signal processing, signals displayed on the Scope block are stored in variables.

Wind Turbine (VAWT): Designed (Figure 9) to model the conversion of wind energy based on given wind speeds and specific turbine attributes. A AC/DC converting process is stabilizing finally the DC Bus to 48V (PMSG—Universal Bridge)-DC/DC.

Hydro Pump: This module (Figure 10) signifies the mechanism wherein energy is stored as gravitational potential energy. The hydro pump is activated to lift water, which, when released, is converted back to generate electricity. The load is the Drilling pump load and the breaker controls the on/off operation. The function is as simple as

```
(function circuitBreakerOutput = controlCircuitBreaker(batteryCapacity)
  if batteryCapacity > 99
        circuitBreakerOutput = 1;
  else
        circuitBreakerOutput = 0;
  end
end)
```

Battery Storage System with BMS: An intricate simulation (Figure 11) of electrical energy storage and retrieval. It considers battery capacity, state of charge, discharge/charge rates, and health monitoring via the BMS.

DC Bus: Acts as a core centralized point interconnecting all RES and the battery system, functioning as the primary energy distribution junction (Figure 12).

DC/AC Inverters & VSC Controller: These components transition the DC power derived from RES and battery systems into AC power, compatible with residential and commercial utilities.

AC Drilling Pump: A mechanism that drives water extraction processes, refilling the hydro pump tank and playing a pivotal role in fine-tuning energy levels.

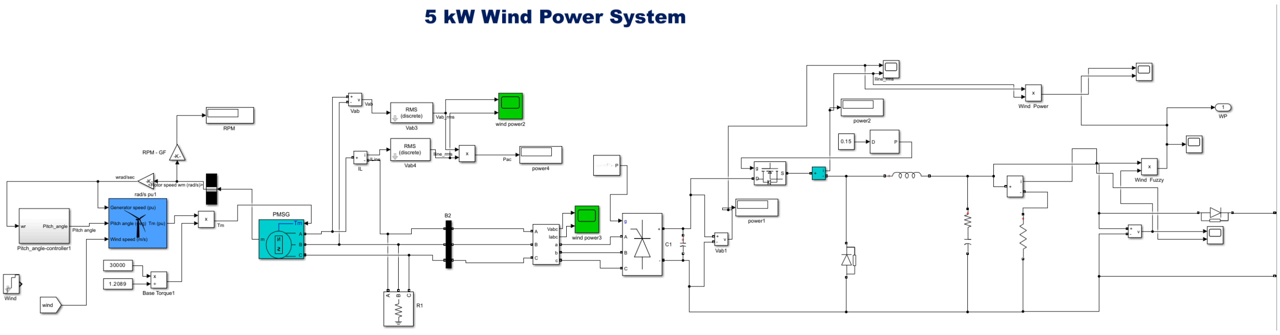


Figure 9. Wind turbine AC/DC/DC circuit.

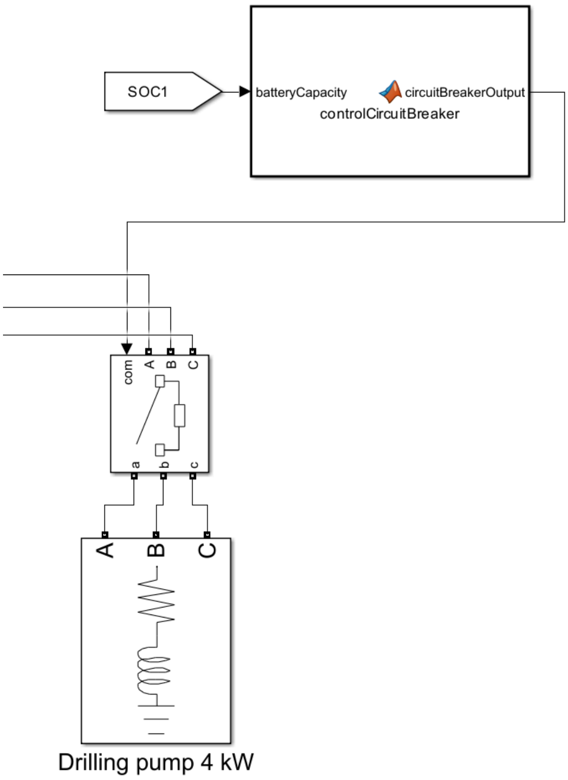


Figure 10. "Hydro pump" & drilling pump simulation.

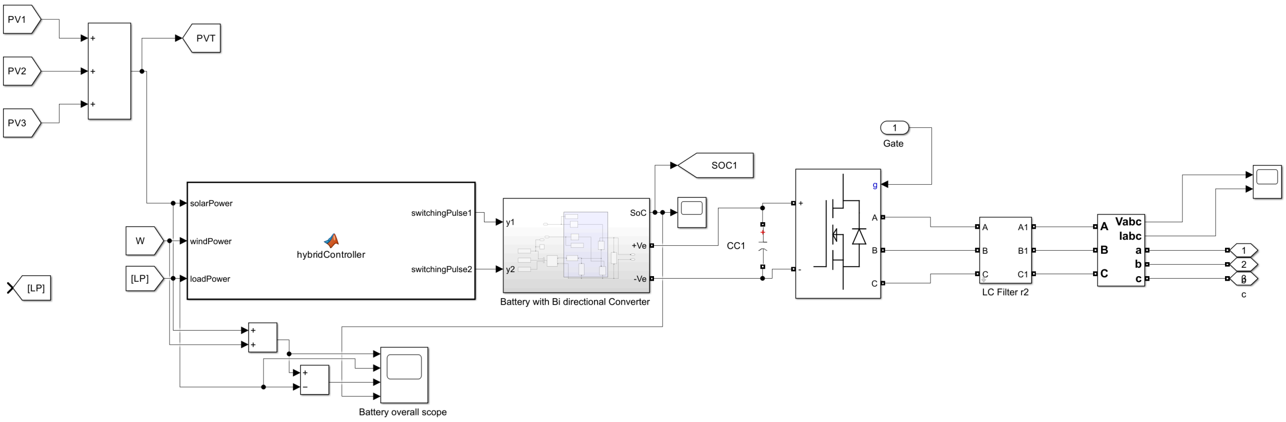


Figure 11. BMS battery system.

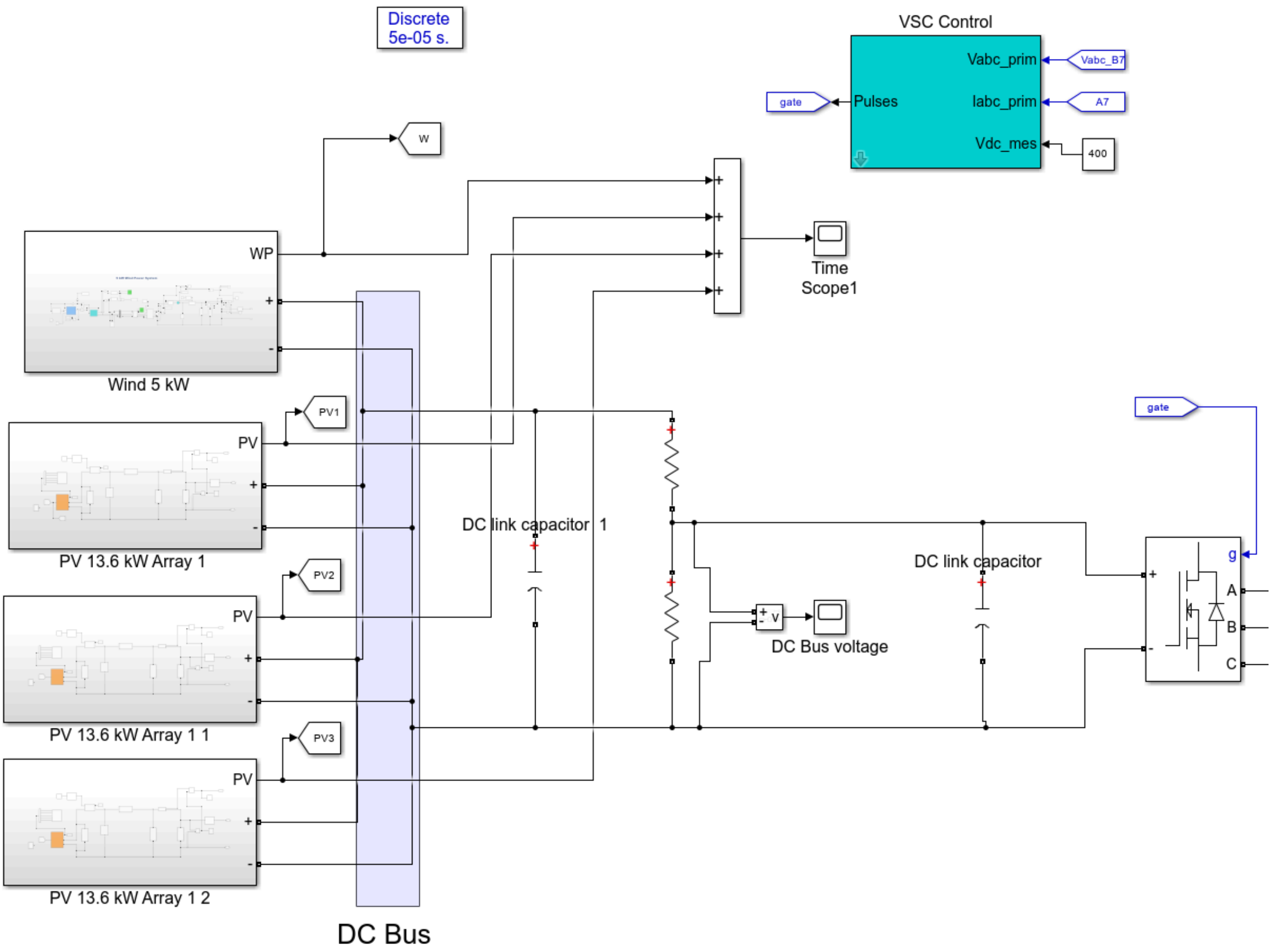


Figure 12. DC bus.

Critical and Normal Loads: Representing primary and secondary electrical consumers, the model (**Figure 13**) dynamically orchestrates the energy supply to these sectors based on availability and controller directives.

Grid Interface: Allows for two-way communication and power transfer between the micro-grid and the main electrical grid (**Figure 14**).

Inputs and Outputs:

Inputs:

- Solar Irradiation data
- Ambient Temperature
- Wind Speed
- Initial State of Charge (Battery)
- Load Profiles for Critical and Normal loads

Outputs:

- Component-Specific Energy Production/Consumption over Time
- Battery State of Charge Monitored via BMS
- Hydro Pump Tank Water Level (Energy Storage in KWh)
- Status Check on Critical and Normal Loads (On/Off)
- Grid Interaction Data (Power Drawn from or Fed to the Grid)

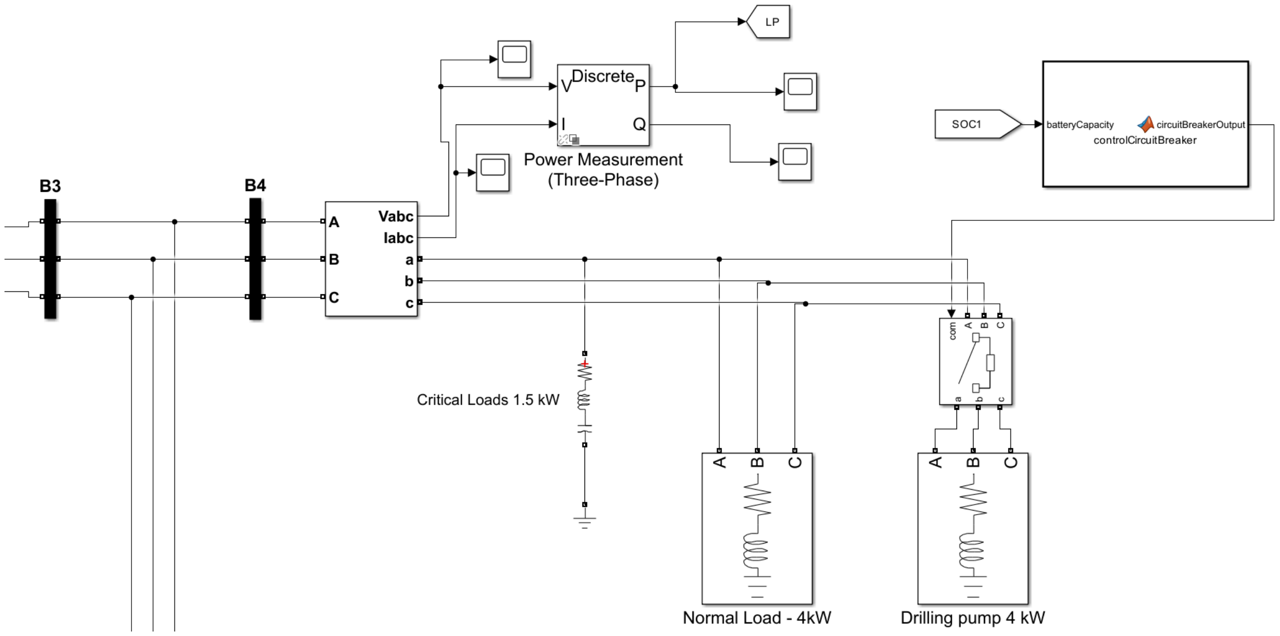


Figure 13. Loads (critical & normal).

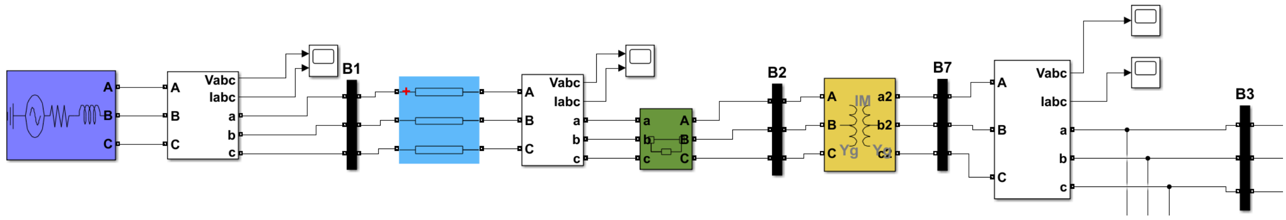


Figure 14. Grid.

Control Strategies:

Central to the model, the AmEFC controller is meticulously designed to ensure an unbroken power supply to critical loads across varied scenarios. It assesses real-time data inputs from interconnected systems, synergizing this information with sophisticated algorithms to make instantaneous energy distribution decisions. These decisions span across energy storage, utilization, prioritization of certain RES, momentary disconnection of non-essential loads, and grid interactions.

Interconnections:

The DC bus is the keystone of the prototype, linking all RES, the BMS-equipped battery storage system, and the inverters. The inverters subsequently connect to the AC loads, AC drilling pump, and the main electrical grid.

Simulation Settings:

Depending on the simulation's objectives and the data's granularity, the time step can be calibrated accordingly. Solvers like "ode15s" are generally efficient for power system simulations. Typically, the simulation spans between a single day to multiple days, encapsulating the micro-grid dynamics through diverse scenarios.3.9.5. Dynamic Discharge Management: In situations where there's excessive wind energy, and batteries are at peak capacity, the system disconnects the wind turbine, rerouting the excess.

3.11.2. Running the Simulink Model

Scenario Analysis: Reliability and Surplus Energy Management in the AmEFC Micro-grid System.

The Objective is to validate the system's reliability in consistently powering critical loads and efficiently utilizing surplus energy through hydraulic energy storage, ultimately gauging its responsiveness during battery discharge phases.

Components under Test:

Critical Loads:

These are the primary focus of this scenario, representing essential appliances and services that cannot afford a power interruption.

Drilling Pump and Water Tower:

The drilling pump transfers water to the storage tank, converting surplus electrical energy into potential energy.

The hydro pump recovers this energy, converting the potential energy back to electrical energy when the battery is in a discharge state.

Battery and BMS:

The battery's state of charge, as monitored by the BMS, plays a pivotal role in the decision-making process. It aids in determining when to initiate energy storage in the water tower and when to draw from the hydro pump.

The simulation starts with the AmEFC system in an operational state, generating power from available renewable sources.

Surplus Energy Detection:

As the renewable energy sources generate electricity, the system continually satisfies the critical load requirements. Any excess energy, after catering to the critical loads and charging the battery to its optimum level, is identified as surplus.

Energy Storage through Drilling Pump:

The AmEFC controller activates the drilling pump upon detecting surplus energy. The pump transfers water into the storage tower, converting this surplus electrical energy into gravitational potential energy.

Battery Discharge Monitoring:

When the renewable sources are insufficient, and the battery starts discharging to cater to the critical loads, the BMS provides real-time data about the battery's state of charge.

Hydro Pump Activation:

Once the battery reaches a predetermined discharge level, the AmEFC controller prompts the hydro pump into action. This hydro pump "releases water from the storage tank", converting the stored potential energy back into electricity, thus supplementing the energy requirements of the critical loads.

Evaluation Metrics:

- Continuity: The uninterrupted operation of critical loads throughout the simulation period.

- Energy Conversion Efficiency: The efficiency in converting surplus electrical energy to potential energy and vice versa.
- Response Time: The system's agility in detecting the need and transitioning between different energy sources and storage mechanisms.

Through this scenario, the system's ability to seamlessly transition between different energy storage and generation methods, all while ensuring uninterrupted power to critical loads, will be established. The irradiation and PV production accordingly to the wind speed and VAWT production is presented in **Figures 15-17**).

In **Figure 18** the normal loads feeding is presented on the top off the critical loads, when the level of energy capacity satisfies the conditions. In **Figure 19** there are from top to bottom, th PV & WT power, the critical + normal loads feeding, the Power production and finale the battery charging/discharging levels.

4. Analyzing Results and Discussion

The pioneering design of the AmEFC micro-grid system is anchored around three primary energy producers: the Photovoltaic (PV) System, the Vertical Axis Wind Turbine (VAWT), and the Hydro Pump-based Water Tower. An essential aspect to understand before diving into the system's performance analysis is its initialization stage, characterized by zero energy production or storage. This stage serves as the reference point, laying the foundation for evaluating how the

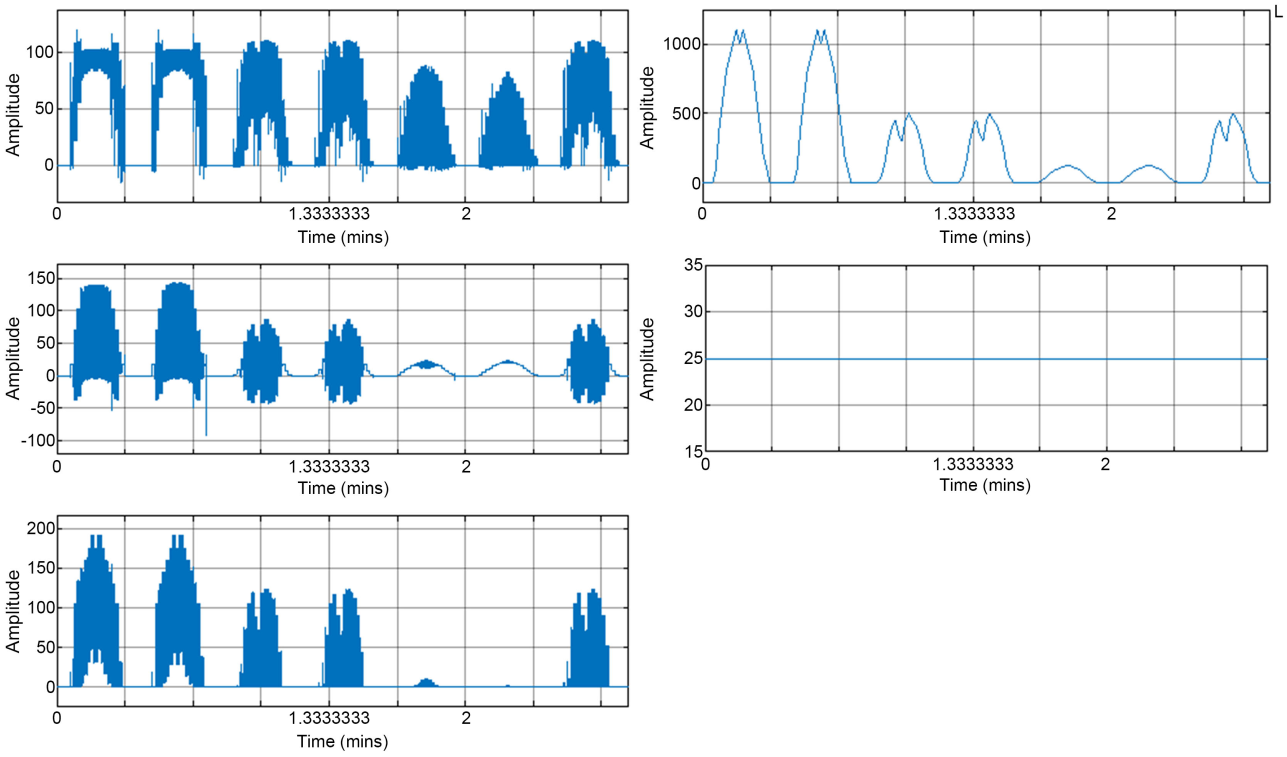


Figure 15. PV system array (irradiation, production).

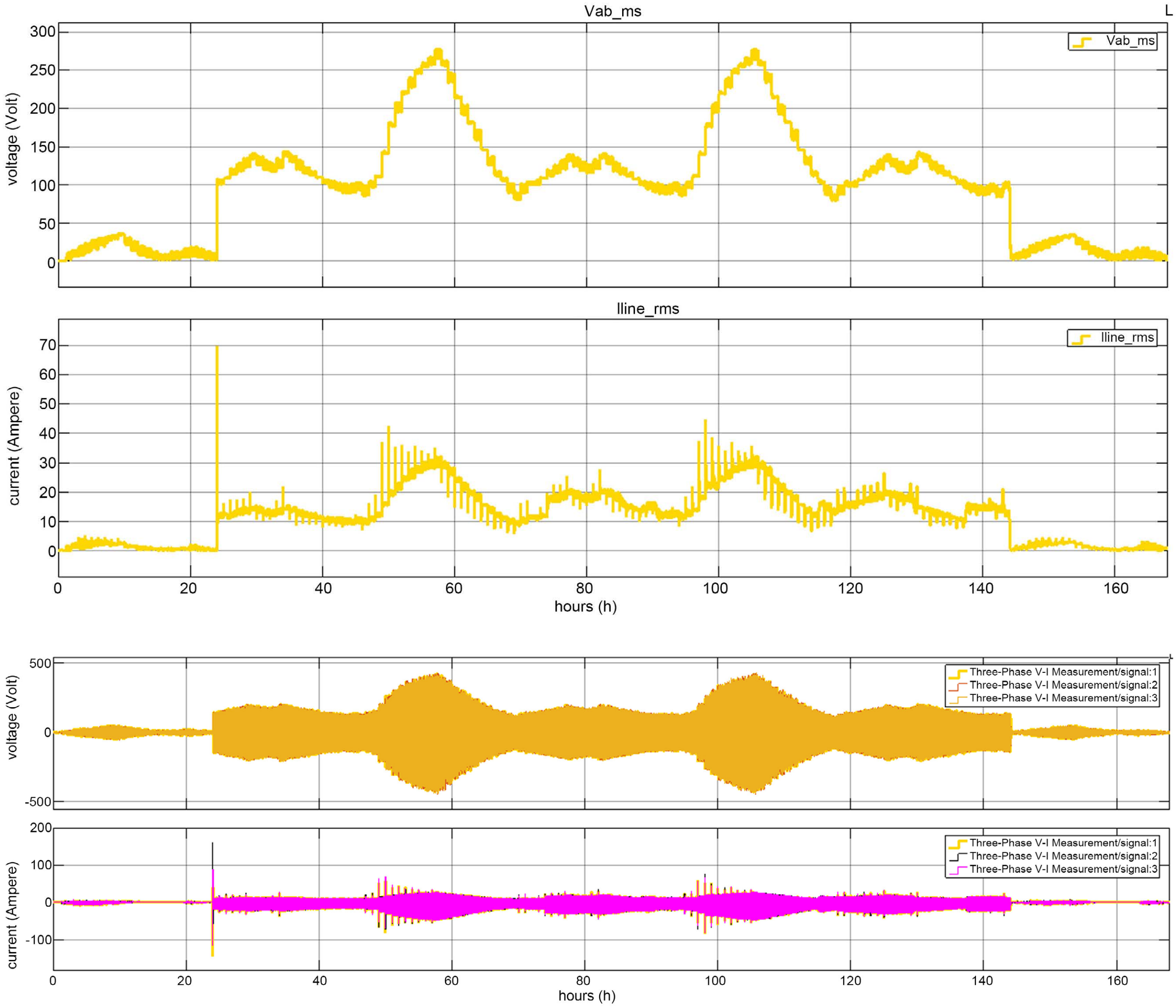
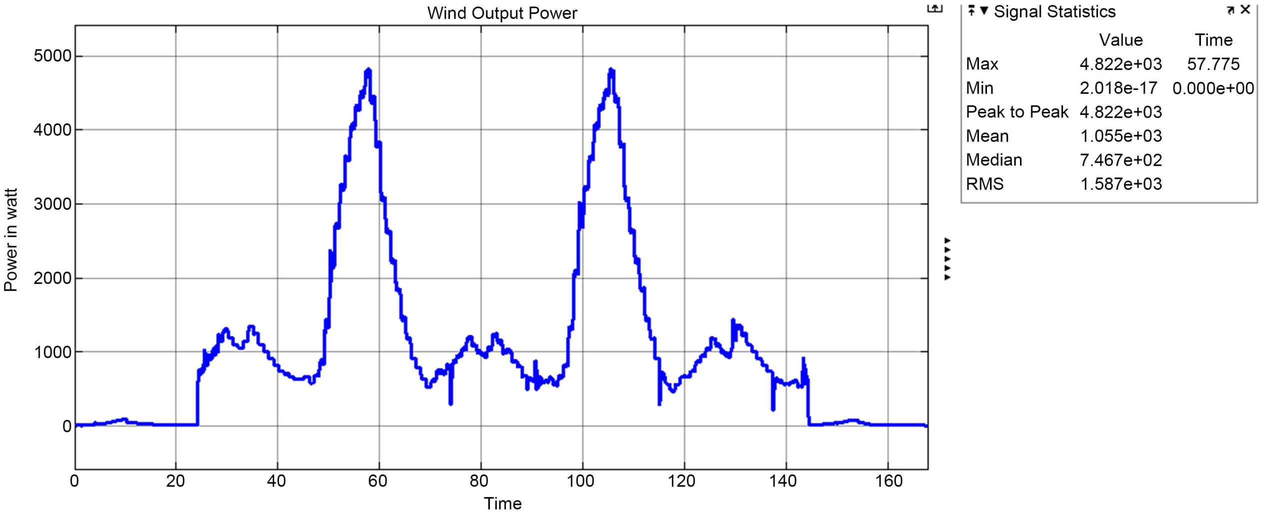


Figure 16. Wind turbine diagrams (wind, production).



	Value	Time
Max	4.822e+03	57.775
Min	2.018e-17	0.000e+00
Peak to Peak	4.822e+03	
Mean	1.055e+03	
Median	7.467e+02	
RMS	1.587e+03	

Figure 17. Wind turbine power statistics.

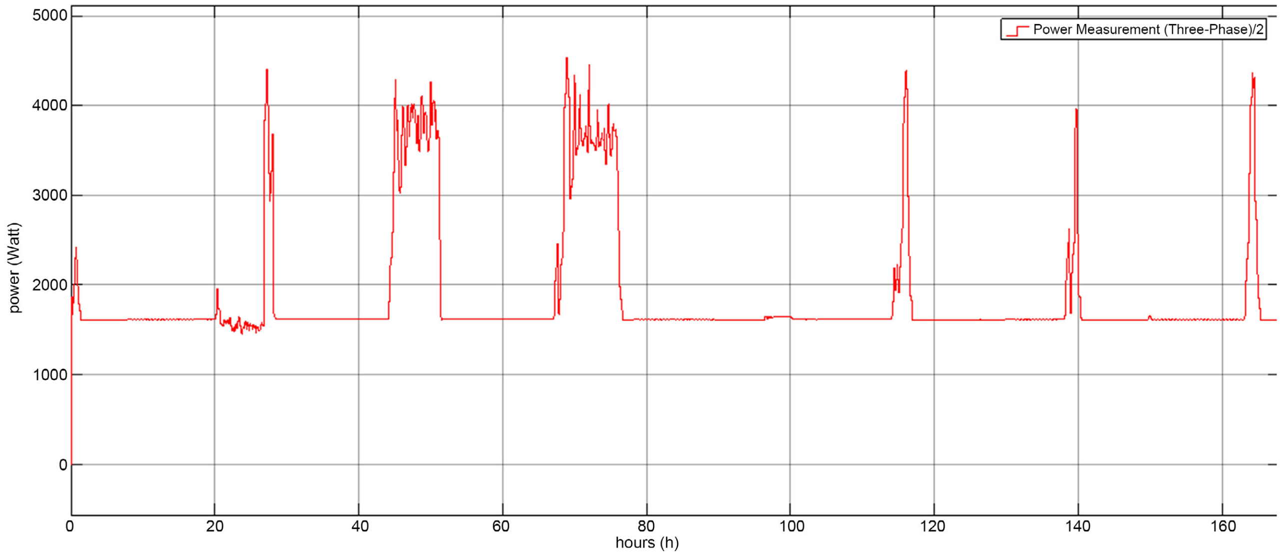


Figure 18. Critical loads (1.5 KW) adding normal loads (4 KW).

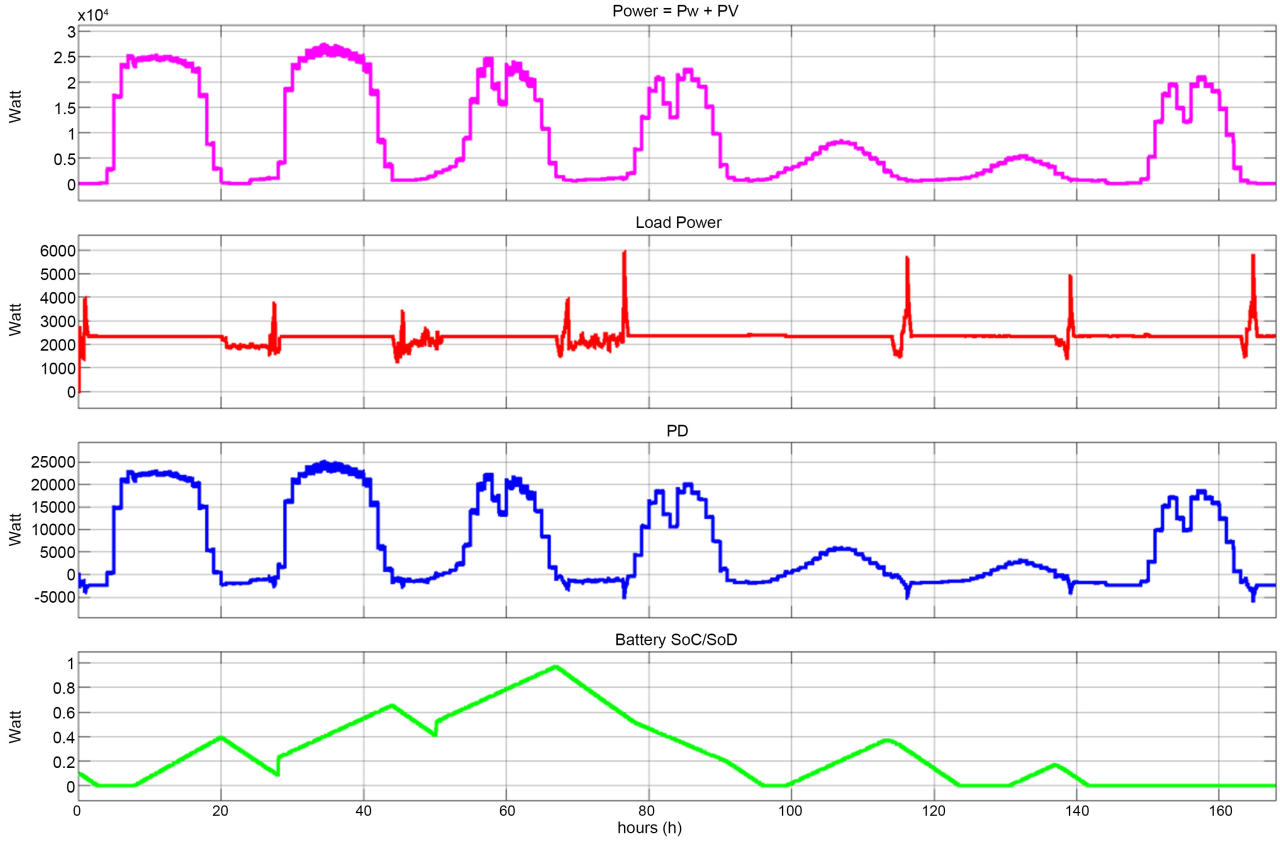


Figure 19. Overall measurements.

system responds to various external environmental stimuli. The system's adaptability and efficiency can be best observed when subjected to a range of weather conditions. To delineate this, we categorize the weather scenarios based on two pivotal factors: solar irradiance and wind speed. These factors are further segmented into three distinct categories (**Table 2**) for comprehensive analysis:

Table 2. Domain various values for sun irradiation and wind speed.

Various values		Sunshine & wind			
Sunshine (w/m^2) high	Wind (m/sec) high	Sunshine (w/m^2) medium	Wind (m/sec) medium	Sunshine (w/m^2) low	Wind (m/sec) low
0	4.1	0	3.8	0	0.3
0	5.2	0	4.0	0	0.4
0	6.5	0	4.3	0	0.5
0	7.3	0	4.5	0	0.7
100	8.0	10	4.7	10	0.8
400	8.5	50	5.0	30	0.9
600	9.0	150	4.8	50	1.0
800	9.3	300	4.6	70	1.1
900	9.5	400	4.5	90	1.2
1000	9.8	450	4.7	100	1.3
1100	9.4	350	5.1	110	1.0
1000	8.7	300	4.9	120	0.8
1100	7.8	450	4.6	130	0.6
1000	7.2	500	4.4	120	0.5
900	6.6	450	4.2	110	0.4
800	6.0	420	4.0	100	0.3
600	5.3	350	3.8	90	0.3
400	4.8	250	3.7	60	0.4
200	4.2	100	3.6	40	0.4
100	3.9	40	3.5	20	0.5
0	3.5	5	3.5	10	0.6
0	3.2	0	3.6	0	0.5
0	3.5	0	3.4	0	0.4
0	3.8	0	3.7	0	0.3

Types of solar irradiance and wind speed.

Solar Irradiance:

A. High Sunshine Day

B. Moderately Sunny Day

C. A Little Sunny Day

Wind Speed:

A. High Wind Day

B. Moderately Windy Day

C. A Bit Windy Day

The subsequent sections will delve into the detailed interplay between these environmental conditions and the corresponding energy production, unveiling the robustness and responsiveness of the AmEFC micro-grid system.

In **Figure 20** the corresponding irradiations of a high sunshine, moderately sunny and a little sunny day is presented on left side, as such as wind speed of high wind, moderately windy and a bit windy day is presented on the right.

4.1. Week-Long Simulation Sequence for AmEFC Micro-Grid Systems Testing

To rigorously test the AmEFC micro-grid system and, more crucially, the operational efficiency of the controller, a comprehensive week-long simulation was devised. The simulation was structured to cover a myriad of environmental conditions by intertwining the aforementioned solar and wind categories. The sequence provides a holistic view, encompassing both optimal and challenging conditions to gauge the system's adaptability, resilience, and efficiency.

Here's the introduced sequence for the week:

Day 1: High Sunshine Day (Category A) paired with High Wind Day (Category A).

Day 2: High Sunshine Day (Category A) combined with Moderately Windy Day (Category B).

Day 3: Moderately Sunny Day (Category B) combined with High Wind Day (Category A).

Day 4: Moderately Sunny Day (Category B) paired with Moderately Windy Day (Category B).

Day 5: A Little Sunny Day (Category C) paired with High Wind Day (Category A).

Day 6: A Little Sunny Day (Category C) combined with Moderately Windy Day (Category B).

Day 7: Moderately Sunny Day (Category B) paired with a bit Windy Day (Category C).

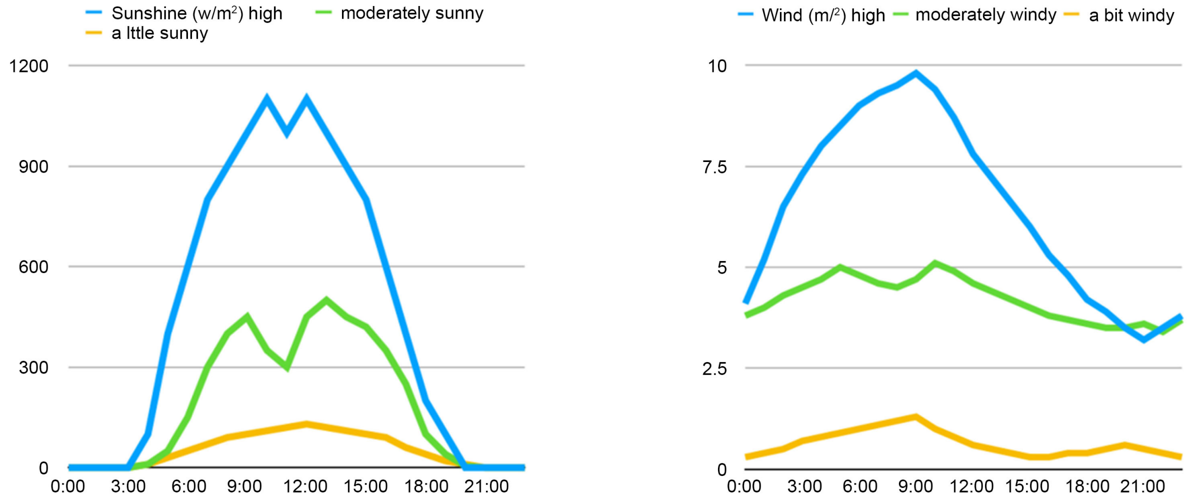


Figure 20. Sun irradiations and wind speeds on various days (blue very sunny and windy, blue moderate and orange a bit).

This sequence, featuring an amalgamation of varying solar irradiance and wind speeds (**Figures 21-24**), forms the backbone of the simulation. The resulting data, arising from this blend of conditions, will furnish insights into the AmEFC system's capability to adapt and optimize energy flows, thereby underlining its real-world applicability and robustness.

We present a series of graphs that vividly illustrate the interplay between the primary environmental factors—solar irradiation and wind speed—and the resultant energy production in the AmEFC micro-grid system. These visuals stem

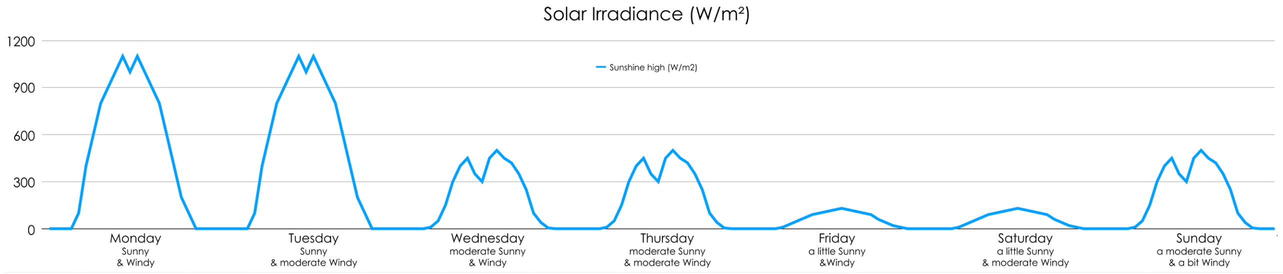


Figure 21. Sun irradiation for a week-long period, daily.

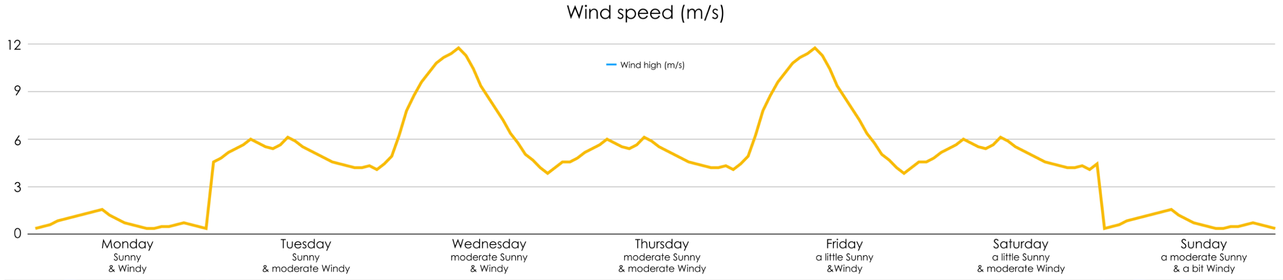


Figure 22. PV system production according to sun irradiation.

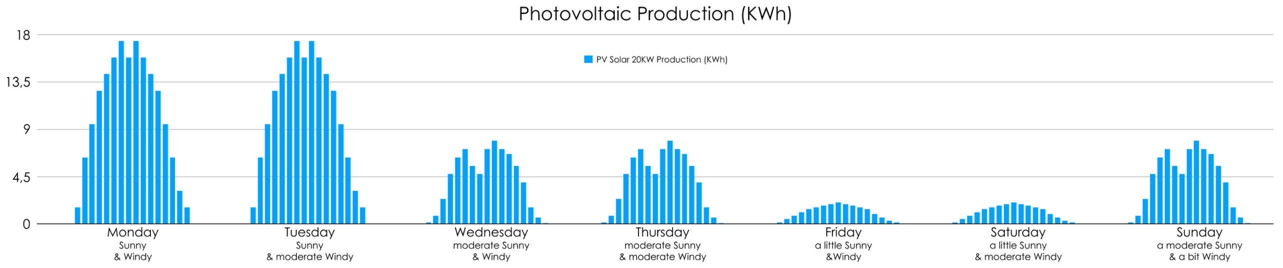


Figure 23. PV system production according to sun irradiation.

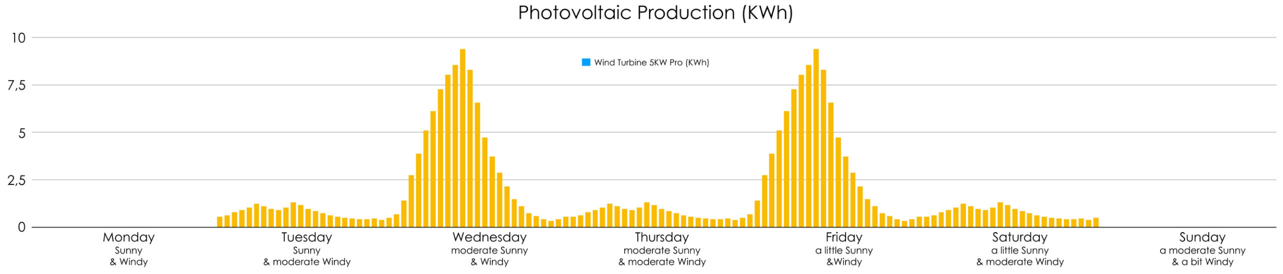


Figure 24. VAWT production according to wind speed.

from a week-long observation, where days were categorized based on their solar and wind profiles. This classification not only simulates the system's response under varying real-world conditions but also underscores the versatility and efficiency of the AmEFC controller. Each graph is designed to offer a granular view of the daily trends, peaks, troughs, and anomalies, providing a comprehensive understanding of how the system navigates through these varying energy input scenarios to maintain optimal energy distribution running various scenarios.

4.2. Testing Scenarios for the AmEFC Controller

To validate the efficiency and adaptability of the AmEFC controller within diverse operating environments, using math and numbers from Appendix B, we have curated for distinct scenarios. Each of these scenarios progressively introduces added complexities and functionalities, simulating both typical and atypical conditions for the micro-grid system.

4.2.1. Scenario 1: Off-Grid Operation without Weather Forecasting & without Water Tower

In this initial and "naked" setup, the micro-grid operates entirely in isolation, without any external data inputs like weather forecasts. The primary objective of the AmEFC controller in this scenario is straightforward—manage the energy production from the RES efficiently and channel losing all surplus energy. This scenario (**Figure 25**) represents a basic, test of the system's autonomous energy management capabilities.

Without weather forecast the system fails to keep critical loads on line (**Figure 26**). Espe-cially without any surplus storage on Water tower there are many cut offs.

4.2.2. Scenario 2: Off-Grid Operation without Weather Forecasting

In this rudimentary setup, the micro-grid operates entirely in isolation, without any external data inputs like weather forecasts. The primary objective of the AmEFC controller in this scenario is straightforward—manage the energy pro-duction from the RES efficiently and channel any surplus energy directly to the water tower for storage. This scenario (**Figure 27**) represents a basic, yet essential, test of the system's autonomous energy management capabilities.

Without weather forecast the system fails to keep critical loads on line, even if it stores energy on Water tower (**Figure 28**).

4.2.3. Scenario 3: Off-Grid Operation with Weather Forecasting Integration

Building upon the previous setup, this scenario integrates real-time weather forecasting data into the system. With this addition, the AmEFC controller is not only managing the energy production and storage but also preemptively adjusting energy distribution strategies. By predicting potential energy production shortfalls or surpluses based on weather data, the controller can ensure uninterrupted power supply to critical loads. Simultaneously, it may choose to temporarily disconnect normal loads as a strategic move to conserve energy during forecasted low-production periods (**Figure 29**).

The weather forecast capability keeps the system safe for the critical loads, using energy on Water tower for fine tuning turning off the normal loads when necessary (**Figure 30**).

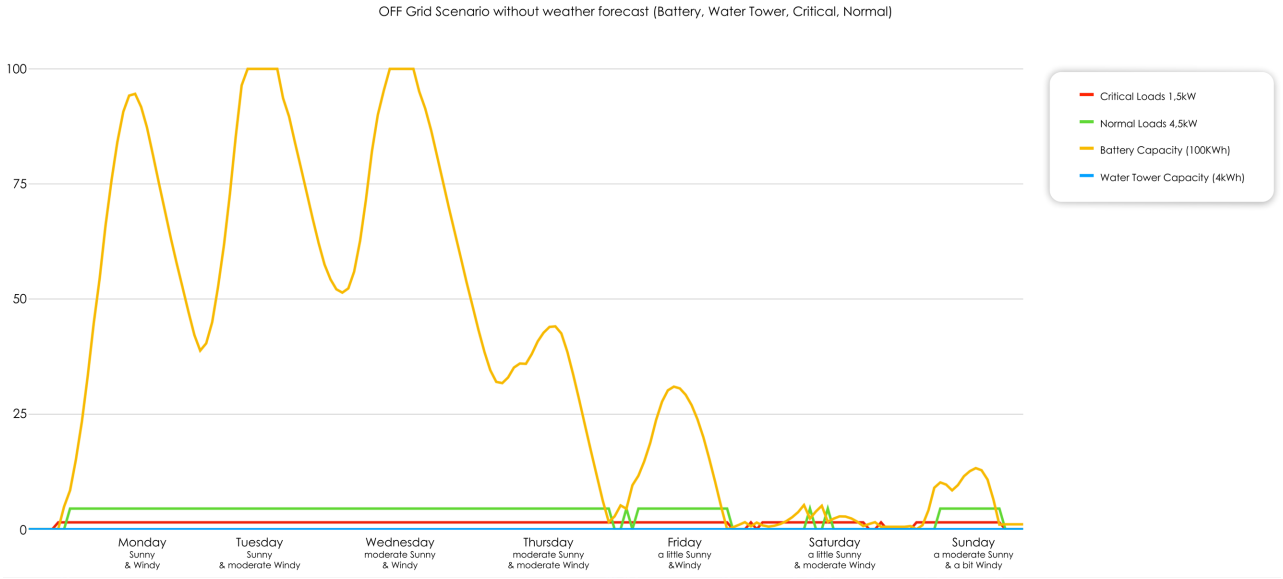


Figure 25. Off-grid operation without weather forecasting & water tank (battery orange, water blue, critical red, normal green).

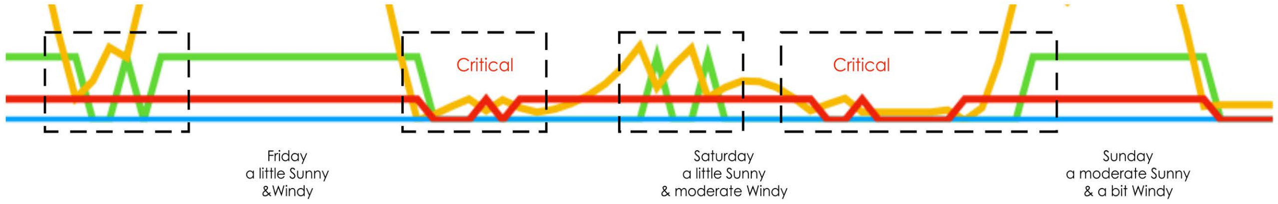


Figure 26. Critical loads often failure without weather forecasting.

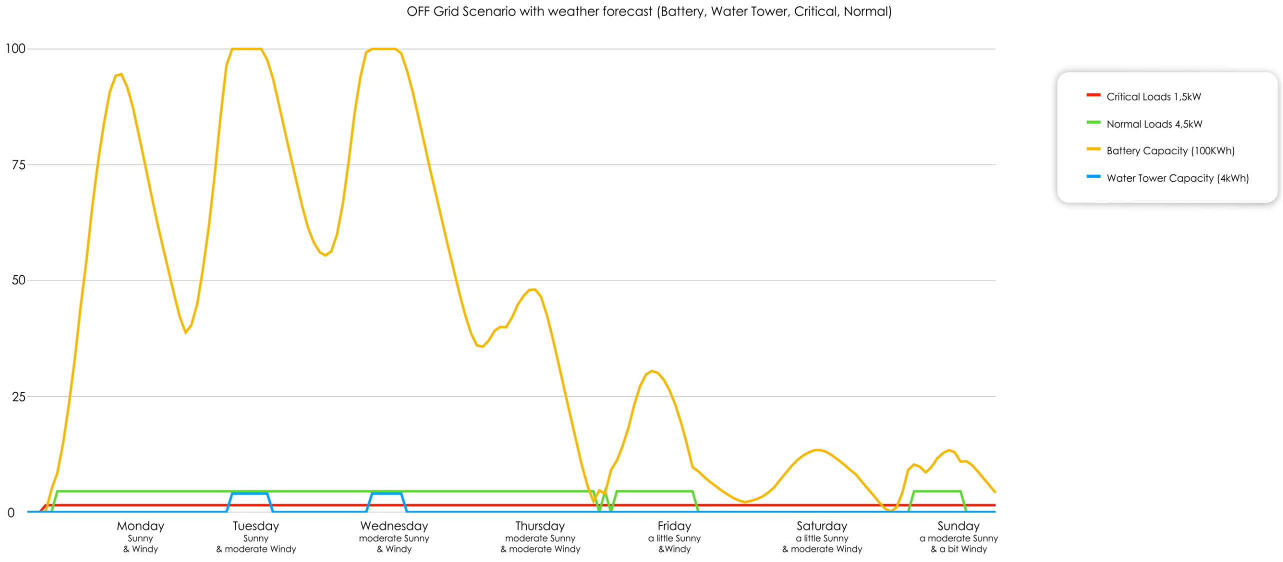


Figure 27. Off-grid operation without weather forecasting (battery orange, water blue, critical red, normal green).

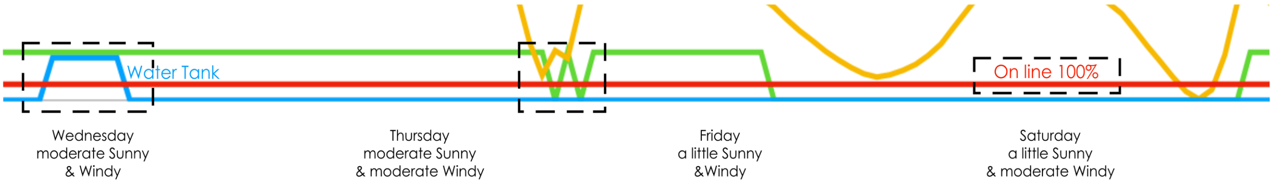


Figure 28. Water tower surplus storage and critical loads failure.

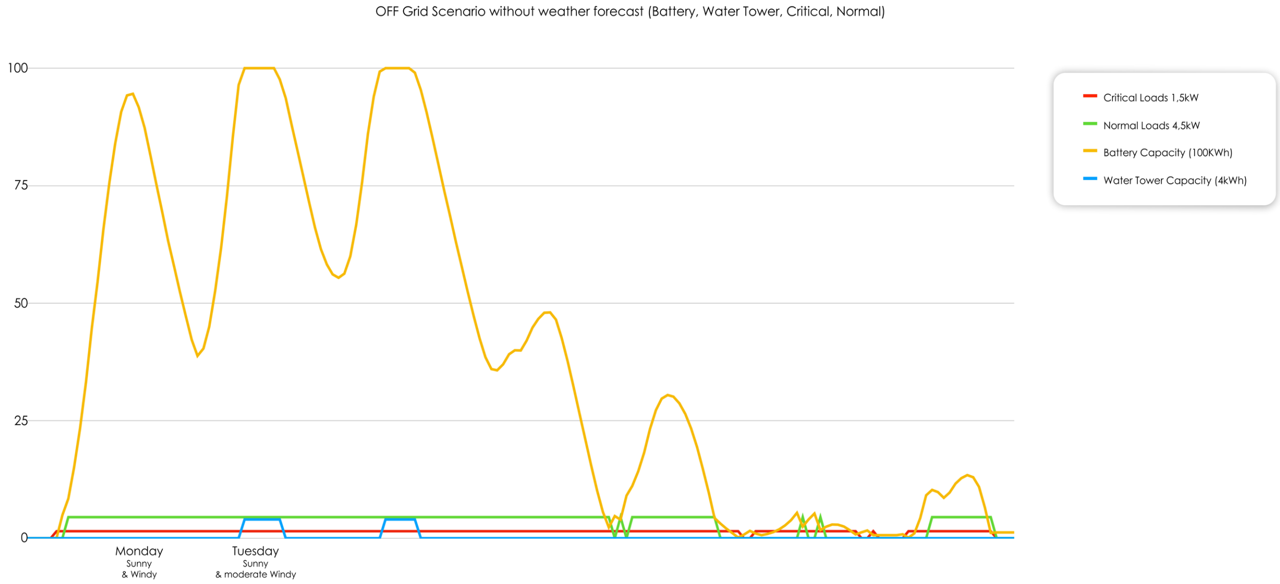


Figure 29. Off-grid operation with weather forecasting (battery orange, water blue, critical red, normal green).

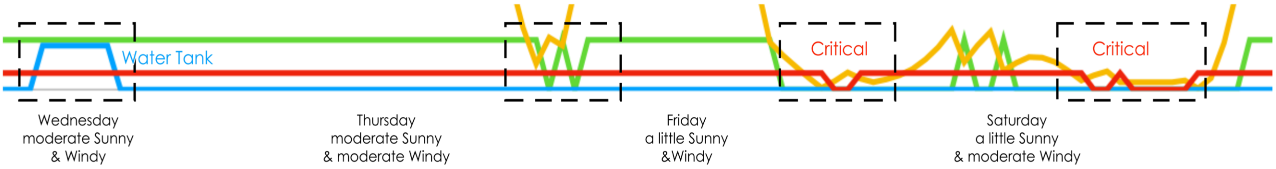


Figure 30. Water tower surplus storage, critical loads on-line 100%, normal loads on & off.

4.2.4. Scenario 4: Hybrid Operation with Grid Connectivity

The final and most sophisticated testing scenario introduces the capability to connect the micro-grid with the larger city-scale grid. In this setup, the AmEFC controller dynamically manages energy surplus by making decisions between storing energy in the water tower or selling it back to the grid. The primary objective is to ensure all loads remain online continuously, reaping the dual benefits of energy storage and potential revenue generation through energy sales. This scenario (**Figure 31**) demonstrates the AmEFC controller's potential in a more integrated energy landscape, where micro-grids can symbiotically interact with larger grid infrastructures.

The on-grid system, keeps critical and normal loads online (100%) with the same priorities using surplus storage in Water tower first and selling the additional surplus (instead of spend it as useless) to PPC (**Figure 32**).

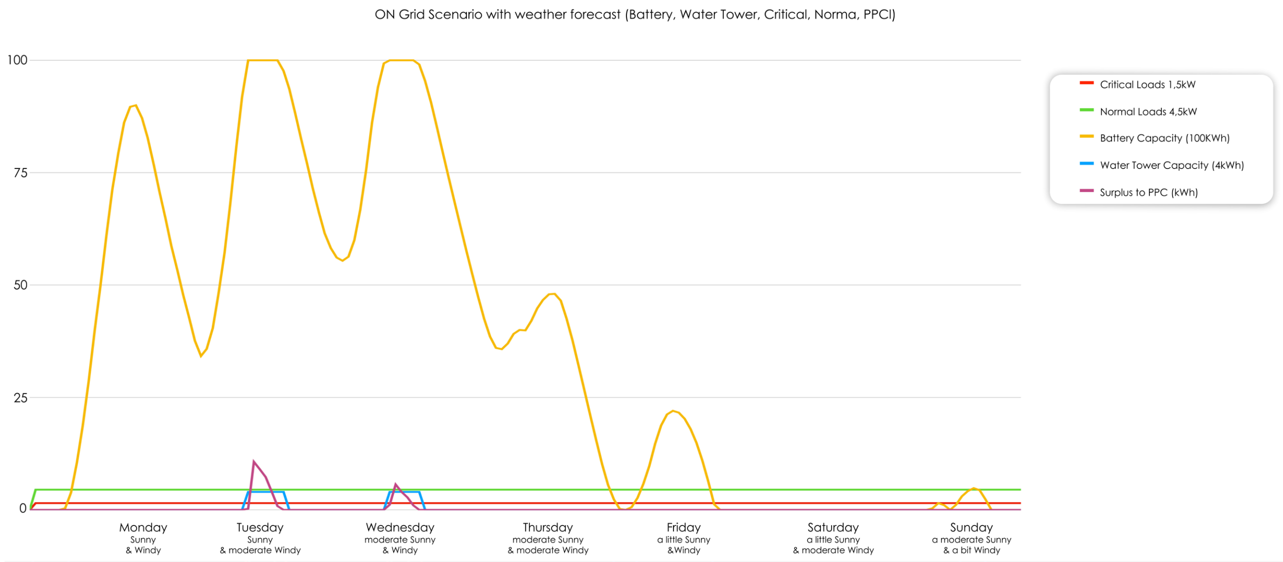


Figure 31. On-grid operation with weather forecasting (battery orange, water blue, critical red, normal green, PPC purple).

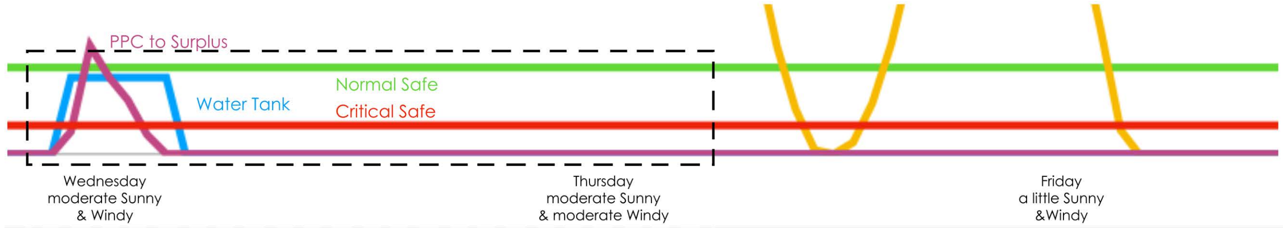


Figure 32. Water tower surplus storage, critical & normal loads on-line 100%, surplus to PPC.

5. Conclusions

The evolution of energy systems to become more sustainable, resilient, and adaptable has been vividly exemplified by the development and validation of the AmEFC (Autonomous multifactor Energy Flow Controller). This research has systematically broken down the multi-level architectural framework of AmEFC, elucidating its capability to balance foundational energy components with advanced decision-making systems. Central to the system's efficacy is the incorporation of diverse Renewable Energy Sources, battery storage mechanisms, dynamic load management, and supplemental energy backup systems, all coordinated by the sophisticated AmEFC controller.

Our Simulink model simulation of the on-grid AmEFC micro-grid prototype distinctly exhibited the system's reliability in consistently catering to critical loads while effectively managing surplus energy through hydraulic storage. Moreover, the intricate interactions within city-scale micro-grids highlighted both the challenges and opportunities, emphasizing the system's adaptability and potential to transform traditional energy grid dynamics. The innovative potential to integrate weather forecasting and real-time decision-making capabilities of the AmEFC controller stands out, potentially revolutionizing the way micro-grids operate and interact on a broader scale.

6. Future Works and Limitations

While the present study has established a solid foundation for the Autonomous Multi-Factor Energy Flows Controller (AmEFC), it is important to acknowledge its limitations which pave the way for future work:

Interconnectivity Limitations: The current AmEFC framework is in its nascent stages, with limited capabilities for complex inter-microgrid communications. To advance this aspect, future efforts will aim to develop robust protocols for inter-microgrid communication, enabling AmEFC controllers to exchange energy resources efficiently and bolster overall grid resilience.

Algorithm Optimization: The existing AmEFC utilizes relatively basic algorithms which may not capture the full spectrum of dynamic variables influencing energy systems. Integrating advanced artificial intelligence and machine learning could substantially refine the controller's predictive capabilities, making energy management more precise and adaptable to changing conditions.

Model Testing Limitations: The Simulink models employed thus far have been limited to standard operational scenarios. It is essential to subject future models to a broader range of conditions, including extreme weather events and equipment failures, to truly assess the system's robustness.

Economic Feasibility: The economic aspect of AmEFC deployment remains unexplored in the current research. To validate the practical viability of this technology, extensive cost-benefit analyses are crucial. Such evaluations must weigh the immediate financial implications against long-term benefits and savings.

Pilot Testing: The reliance on simulations within this research is a notable limitation. To fully understand the controller's efficacy, pilot implementations in real-world settings across various geographic and climatic conditions are necessary. These pilots are expected to provide critical data that can refine the AmEFC for broader and more diverse applications.

In summary, future research will extend beyond the theoretical and simulated realms to address these limitations. By focusing on improved communication protocols, advanced analytical algorithms, rigorous scenario testing, economic analysis, and real-world piloting, the AmEFC can evolve into an even more reliable and sophisticated system ready for the complexities of global energy management challenges.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix A

"Controller's flow chart model".

https://www.researchgate.net/publication/375379481_Appendix_A_Controller's_flow_chart_model

Appendix B

"Model Math & Numbers" (Excel file is included as supplementary material).

https://www.researchgate.net/publication/375379530_Appendix_B_Math_Model_numbers

https://www.researchgate.net/publication/375379495_Appendix_B_AmEFC_numbers_AP_B

Appendix C

"Homer Simulation".

https://www.researchgate.net/publication/375379498_Appendix_C-Homer_simulation#fullTextFileContent