

COST-OPTIMISED DESIGN OF HYBRID SOLAR-WIND-BATTERY POWER SYSTEMS FOR AUTONOMOUS COMMUNICATION TOWERS IN LATVIA

J. Prieditis, S. Gendelis*, R. Pols, P. Bethers, J. Sennikovs

University of Latvia,
Faculty of Science and Technology,
Institute of Numerical Modelling
3 Jelgavas Str., Riga, LV-1004, LATVIA
*e-mail: stanislavs.gendelis@lu.lv

The study presents a computational framework for optimising hybrid solar–wind–battery power systems for autonomous communication towers under Latvian climatic conditions. A Python-based model, incorporating pvlib, windpowerlib, and meteorological datasets (ERA5, NEWA), is used to simulate hourly energy generation, battery state of charge, and system costs across a three-dimensional parameter space of solar capacity, wind capacity, and battery storage. The primary objective is to identify the least-cost configurations that ensure at least 99 % tower uptime. Detailed results are demonstrated for one specific communication tower site in Latvia, where pronounced non-linear behaviour is observed between equipment cost and achievable uptime: initial investments yield rapid reliability gains, while approaching 99 % uptime requires disproportionately higher costs due to rare but prolonged energy deficit periods. For the built experimental reference tower, the globally optimal configuration achieving 99 % uptime includes approximately 36.7 kW of solar PV, 5.9 kW of wind, and 54 kWh of battery storage at a total cost of €45,000, while additional constrained scenarios with fixed existing solar or wind capacity are also evaluated. The results highlight the need for balanced scaling of all three components and provide spatially interpolated maps of optimal system parameters at over 10,000 points, supporting technically and financially sound design of off-grid communication tower solutions in Latvia.

Keywords: *Battery energy storage, communication towers, cost optimisation, hybrid renewable energy systems (HRES), solar photovoltaics, wind power, uptime.*

1. INTRODUCTION

Hybrid renewable energy systems (HRES) that combine two or more energy sources, such as wind and solar power alongside battery storage, have attracted an increasing amount of attention in recent years [1]–[3]. This is primarily due to their potential to reduce carbon emissions, declining technology costs, and the improved reliability that result from the integration of complementary energy sources into a single system [4]–[6]. The production of solar energy is heavily dependent on seasonal cycles and weather patterns, with increased production during summer months and around midday [7]. Wind energy, on the other hand, often exhibits the opposite trend [8], complementing solar generation through higher availability during winter and at nighttime under Latvian climatic conditions [7], [9]. By combining both energy sources and integrating battery storage to mitigate the intermittency of renewable production, HRES can provide a more dependable energy supply, even when neither solar nor wind power generation is immediately available. However, the effectiveness of such hybrid systems depends on appropriate system sizing, local climate conditions, and storage capacity. Therefore, it is crucial to analyse all of these factors when designing such systems.

One area where HRES is particularly promising is in the low-power demand autonomous infrastructure, where energy needs are relatively small, but reliability of operation is still critical [10]. This includes communication towers, environmental monitoring stations, remote sensing equipment, and similar distributed systems that often operate in remote or

isolated locations. In many such cases, connecting to the electrical grid is either too impractical or prohibitively costly, making autonomous energy systems a more appealing alternative. Even in systems with relatively low power demand, ensuring continuous operation is still a challenge, as renewable generation is inherently variable. This is especially significant for communication infrastructure, where even brief interruptions can have major consequences.

These challenges are even more pronounced in regions such as Latvia and the wider Baltic region, where climatic conditions are highly variable and not always favourable for consistent renewable energy production [11]. Solar energy generation is significantly reduced during winter months due to limited daylight and lower irradiance, while wind availability can vary substantially depending on both location and time [7]. There are also noticeable differences within these regions, particularly between inland and coastal regions, with more consistent wind resources along the coast. At the same time, many coastal and offshore locations also lack sufficient grid infrastructure, which further increases practical relevance of autonomous systems in these regions. Given this spatial and temporal variability, a detailed, location-specific analysis is necessary.

Previous research has examined hybrid renewable energy systems across various contexts, often focusing on advanced optimisation techniques and diverse modelling approaches to improve efficiency and reliability of renewable systems [1], [3]. In this study, a computational framework

is developed to optimise hybrid solar–wind–battery systems for autonomous communication towers under Latvian climatic conditions. The model is based on hourly simulations of energy generation and consumption, using meteorological datasets and the power consumption of an existing experimental tower, which serves as a case study representing a real-life communication tower. A wide range of system configurations is explored across different combinations of solar, wind, and battery storage capacities, forming a multidimensional parameter space. The key objective is to identify the least-cost configurations that achieve a high level of

reliability, defined here as at least 99 % uptime.

Additionally, this case study evaluates how system performance varies across the entire area of Latvia, accounting for how location influences renewable potential. The results include performance information for a specific reference site and broader mapping across multiple locations, which identifies regions with higher or lower suitability for such systems. The broader aim is to assess feasibility and to provide practical insight into how these systems could be implemented in real-world conditions.

2. MATERIALS AND METHODS

To model renewable energy power generation and storage, meteorological data from the New European Wind Atlas (*NEWA*) [12] and *ERA5* [13] were used. These datasets contain hourly historical weather data, including wind speed, temperature, solar irradiance, and more, covering the climate period from 1992 to 2021. *ERA5* data, used for solar power calculations, is available at a 0.25-degree spatial resolution (roughly 31 km), while *NEWA*, used for wind resource assessment, offers a much finer grid resolution of 3×3 km.

An experimental communication tower shown in Fig. 1 was built to validate the simulation results. It includes a RyseEnergy E-511 [14] wind turbine at a hub height of 56 meters and Hanersun HN21RN-48HT450W12 [15] photovoltaic panels mounted at a 57-degree tilt angle (Fig. 2). To better distribute generation throughout the day, half of the pan-

els are oriented at a 150-degree azimuth angle, while the other half is oriented at a 210-degree azimuth angle. The Victron Energy SmartSolar MPPT RS 450/200-MC413 [16] charge controller/inverter system is used to ensure energy conversion. For energy storage, the Pytes V5 [17] batteries are used (Fig. 2), as lithium iron phosphate (LiFePO_4) batteries offer high cycle life and are suitable for the Latvian climate’s low temperature conditions, with built-in self-heating functionality.

The consumption profile is based on the energy demand of an analogous communication tower, with an average consumption of 2.1 kW, slightly elevated by the increased energy needs during the evening (Fig. 3). It should be noted that the specific parameters used for these components are not meant to represent a universal solution, but rather serve as a reference case based on an existing real-life communication tower setup.

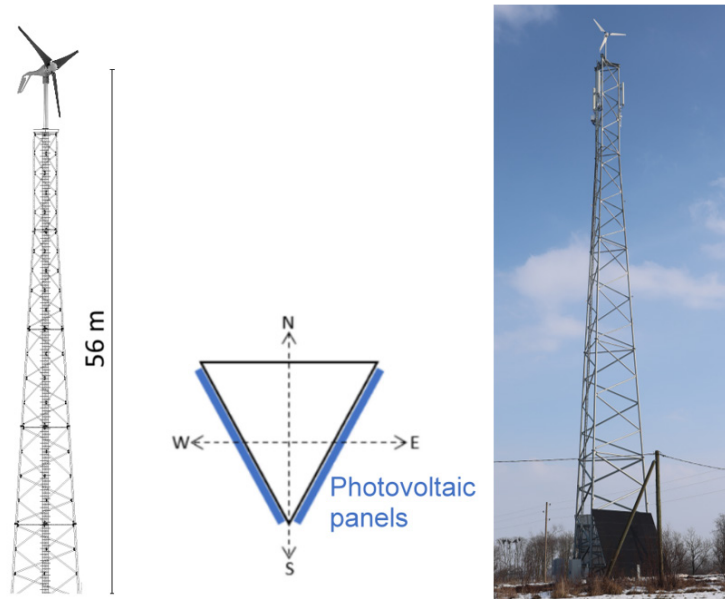


Fig. 1. Schematic of the communication tower configuration and the experimental tower.

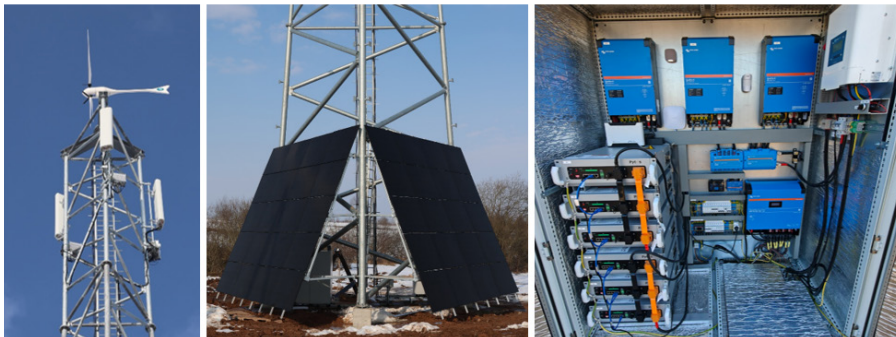


Fig. 2. Components of the experimental communication tower (wind turbine, photovoltaic panels, and batteries).

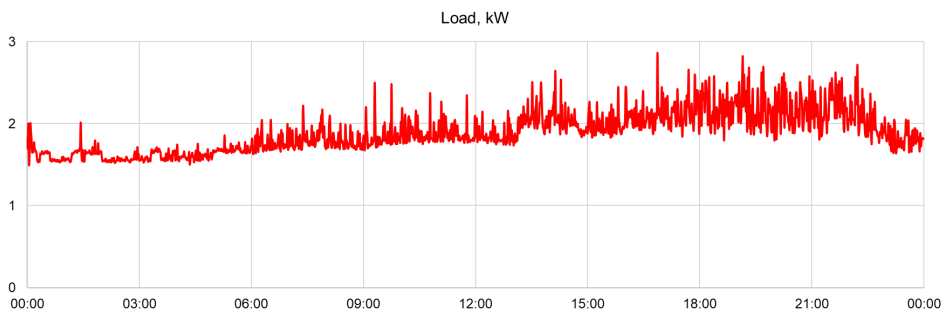


Fig. 3. Typical daily energy demand profile of a communication tower.

Equipment costs are modelled using real-world component prices, normalized per unit (kW, kWh). For solar energy, the total cost of panels and inverters is considered to be 433 €/kW. Wind energy costs are based on a 5-kW turbine priced at approximately 14,500 €, corresponding to 2,900 €/kW of rated power. Battery costs are based on a 5.1 kWh unit priced at 1,200 €, equivalent to 235 €/kWh. These values are used as cost coefficients in the optimisation process, representing the cost of increasing each component in the model.

The simulation model is implemented in Python using the *pvlb* [18] and *wind-powerlib* [19] libraries to model solar and

wind power generation. The model runs at an hourly time step, updating the battery state of charge based on the energy produced by the PV array and wind turbine and the power demand of the telecommunication devices. When generation exceeds demand, surplus energy is stored in the battery (up to its capacity); when generation is insufficient, the battery is discharged to supply the load. If the battery state of charge reaches zero, the hour is counted as an outage event. Figure 4 summarises the computational workflow used to evaluate hybrid systems in terms of uptime (autonomy) and cost.

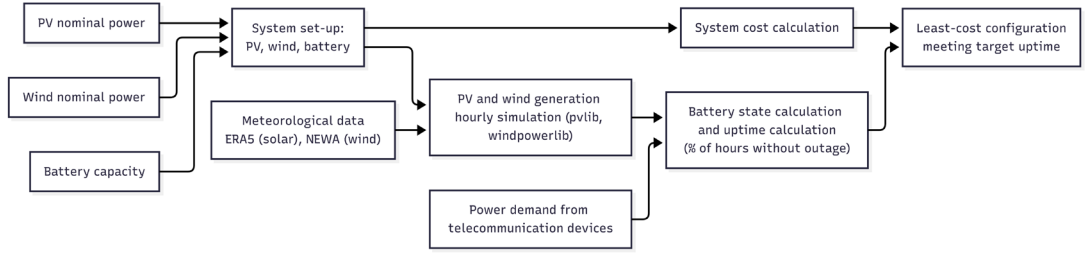


Fig. 4. Computational framework for simulating tower uptime and system costs for hybrid PV–wind–battery configurations.

Total system cost is calculated for each configuration, and the cost–uptime results are used to identify the least-cost configuration

that meets the target uptime requirement.

3. RESULTS

The spatial distribution of optimal system configurations across Latvia shows clear regional differences in both the required system capacities and the total costs. The optimal solar capacity required to achieve 99 % uptime (Fig. 5) indicates

that higher solar generation, up to 45 kW, is required in regions such as the North Kurzeme upland, as well as in central and northeastern Latvia, and in the valleys of the Gauja and Daugava rivers.

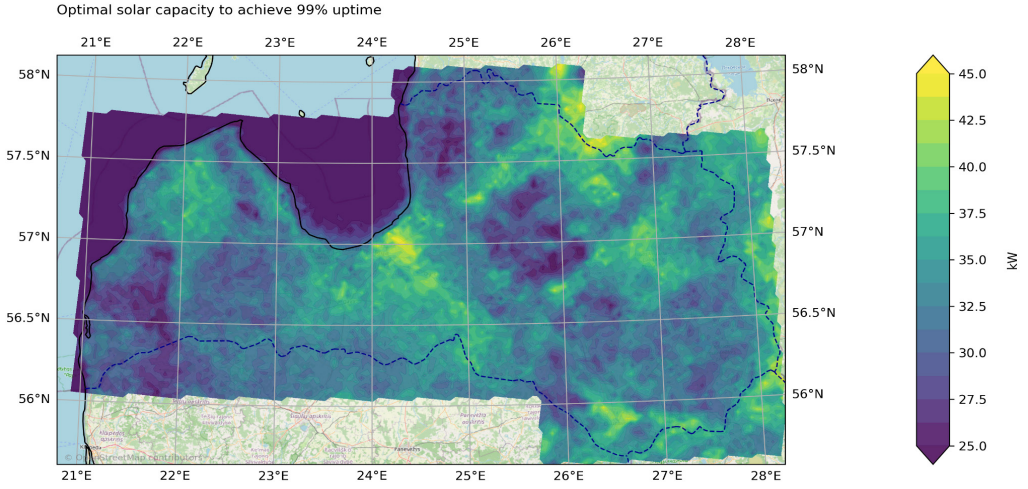


Fig. 5. Optimal solar capacity to achieve 99 % uptime.

In coastal regions, on the other hand, the required solar potential is lower, at about 25–30 kW. Although solar power is much less spatially variable than wind throughout Latvia [20], greater required solar capacity can be explained by the relatively lower wind energy potential, which makes it more difficult to reach the 99 % uptime threshold.

A similar pattern is noticeable for wind capacity (Fig. 6). The highest required

wind capacity of roughly 8 kW is found in regions farther from the coast, where wind resources are less bountiful, whereas closer to the coast, about 5 kW of installed wind power is necessary. In inland locations, compensating for periods of lower solar generation, especially during winter months, becomes more challenging, therefore requiring higher installed wind capacity.

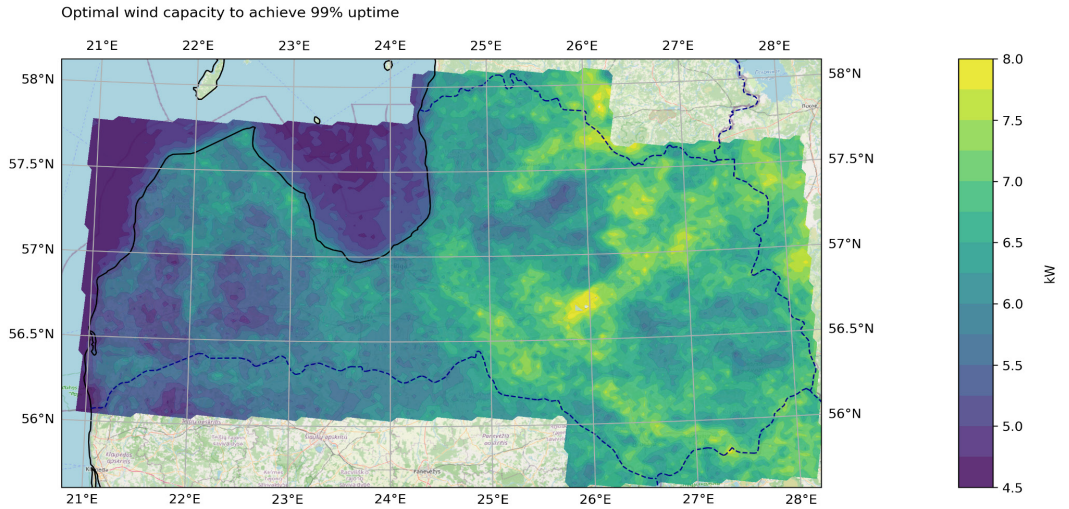


Fig. 6. Optimal wind capacity to achieve 99 % uptime.

The major importance of battery storage is also visible throughout all of Latvia (Fig. 7). In areas with more variable or lower renewable generation, larger battery

capacities of up to 70 kWh, equivalent to about 35 hours of tower consumption, are required to maintain tower uptime.

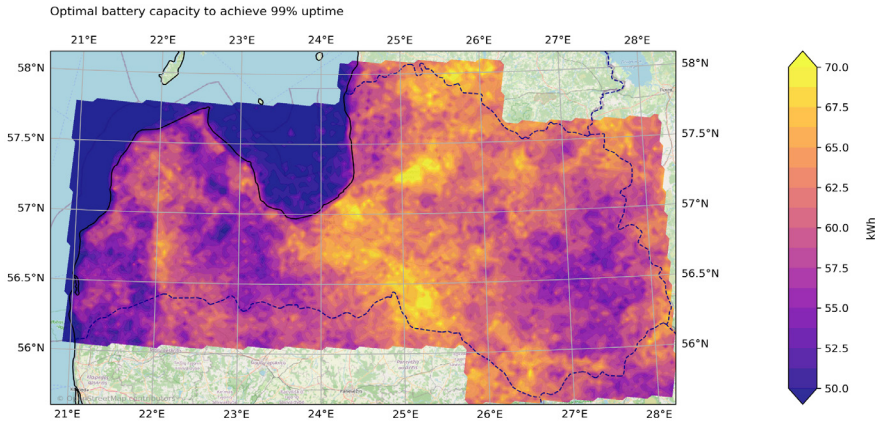


Fig. 7. Optimal battery capacity to achieve 99 % uptime.

This reveals the crucial balance to strike between battery storage and generation capacity, as battery capacity alone does not ensure constant uptime, especially during winter months. Although increased battery storage enables the system to make up for short-term energy deficits, it is crucial for energy generation to be occurring as well.

The total system cost required to achieve 99 % uptime (Fig. 8) assigns monetary value to the previously shown wind-

solar-battery capacities and demonstrates a similar variance across Latvia. In coastal regions, along the Baltic Sea and the Gulf of Riga, the required investment is approximately €40,000, while in regions with lower wind potential, in northeastern Latvia and around the Gauja valley, the required investment increases to €55,000. This represents a nearly 40 % cost variation, highlighting the importance of choosing an appropriate geographic location.

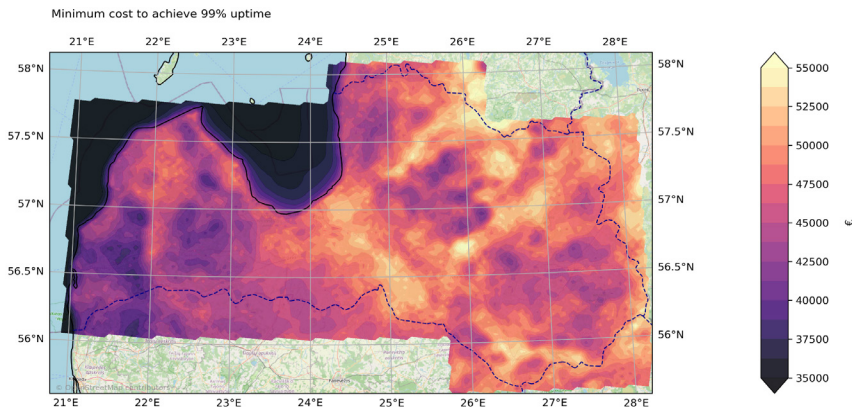


Fig. 8. Minimum cost to achieve 99 % uptime.

To gain a better understanding of how the system's cost manifests, a more detailed analysis is presented for a specific location in western-central Latvia, where the experi-

mental communication tower is built. When examining tower uptime as a function of total system cost (Fig. 9), a clearly nonlinear relationship emerges.

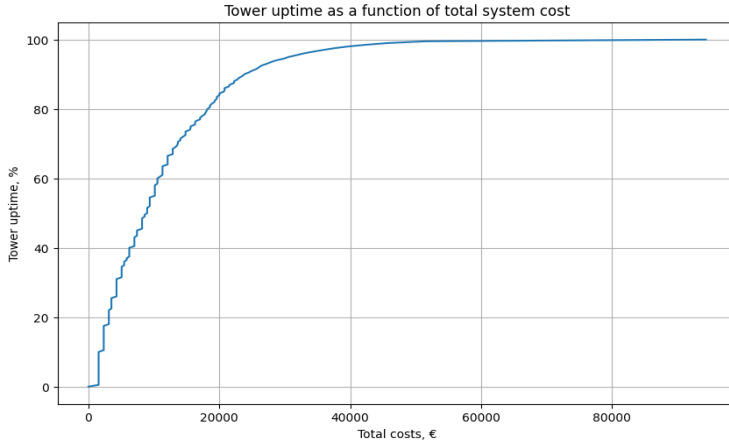


Fig. 9. Tower uptime as a function of total system cost.

At lower investment levels, uptime increases rapidly with even the most marginal additions, whereas as uptime approaches higher values, further improvements become noticeably more expensive. This can be explained by the nature of

energy deficits. The most critical periods are relatively rare but long-lasting. Covering such uncommon periods requires disproportionately large increases in generation or storage capacity, which leads to diminishing returns in terms of cost efficiency.

Optimal hybrid system configurations achieving $\geq 99\%$ uptime (case study site)

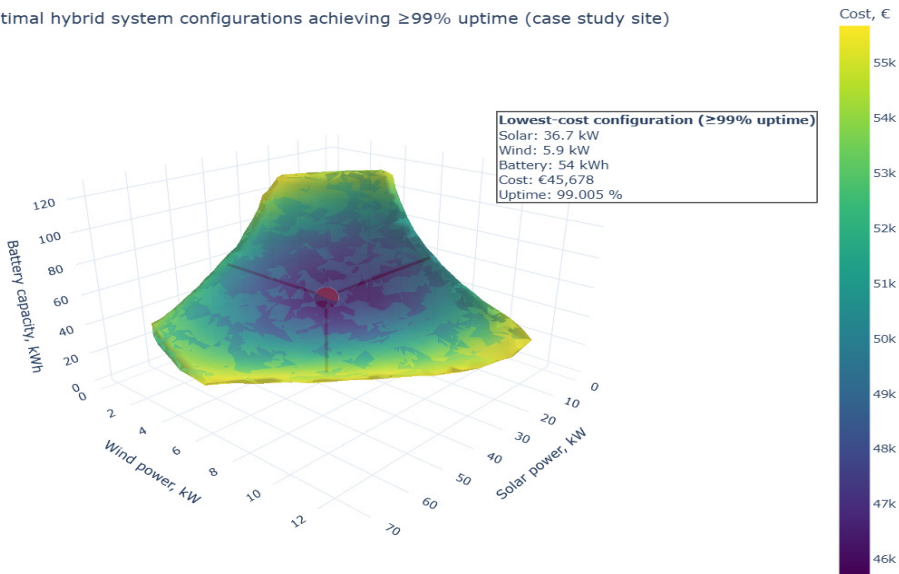


Fig. 10. Optimal hybrid system configurations achieving $\geq 99\%$ uptime for the experimental tower.

The lowest-cost configuration that achieves at least 99 % uptime (Fig. 10) consists of 36.7 kW of solar capacity, 5.9 kW of wind capacity, and 54 kWh of battery storage, with a total system cost of €45,678. This configuration represents the most balanced solution, with all three components increased in a coordinated way, rather than relying too heavily on a single energy source.

When the solar capacity is fixed at the level of the existing tower (18 kW), the optimal configuration shifts to 7.9 kW wind capacity and 74 kWh battery capacity (Fig. 11), with a total cost of €48,318. A similar pattern can be seen when the wind capacity is fixed at its current level of 5 kW: the optimal configuration requires 38.9 kW

solar capacity and 59 kWh battery capacity, resulting in a total cost of €46,616, which is the lowest-cost solution under this constraint. When battery capacity is fixed, the importance of storage becomes even more apparent, with 46.1 kW of solar power and 10.3 kW of wind power required to achieve 99 % uptime, leading to a total cost of €56,842, substantially higher than in the other scenarios. Across all configurations, a similar trend can be observed: the relationship between system cost and uptime is nonlinear, with clear diminishing returns as uptime increases. Therefore, achieving very high reliability using only solar and wind generation and batteries requires a disproportionately large increase in system capacity.

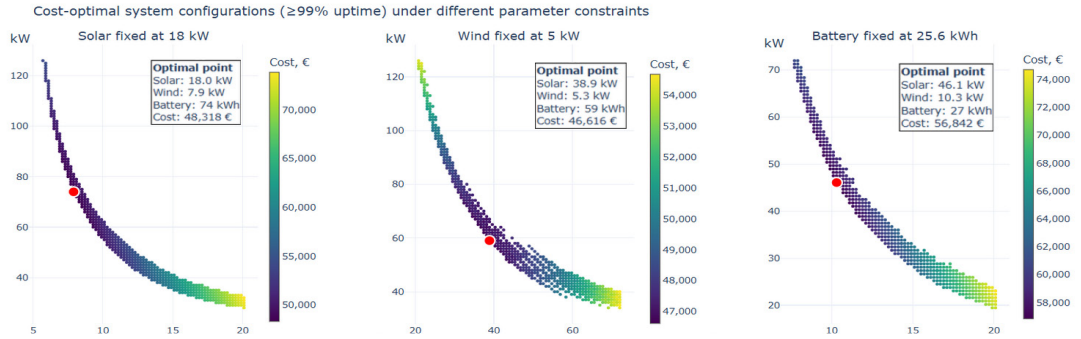


Fig. 11. Cost-optimal system configurations under different parameter constraints.

A real-time afternoon snapshot of the experimental tower's energy flows shown in Fig. 12 indicates predominantly renewable-driven operation, with the load supplied while the battery is charging. At the time shown, the PV arrays produce 7.5 kW (east) and 3.2 kW (west), while the wind source contributes 213 W. This generation is aggregated on the DC bus and used to charge the battery (state of charge (SOC) 82 %, charging at ~8.2 kW) and to supply the inverter, which delivers ~1.8 kW to the

three-phase load. Grid exchange is negligible (19 W), and the backup generator is inactive, implying that the load is largely covered by on-site generation and surplus energy is stored in the battery.

Examples of 24-hour energy production and battery charging profiles for the experimental tower shown in Fig. 13 allow for a visual comparison of wind and solar energy production and battery state of charge under different weather conditions – during a windy day and a lowwind day.

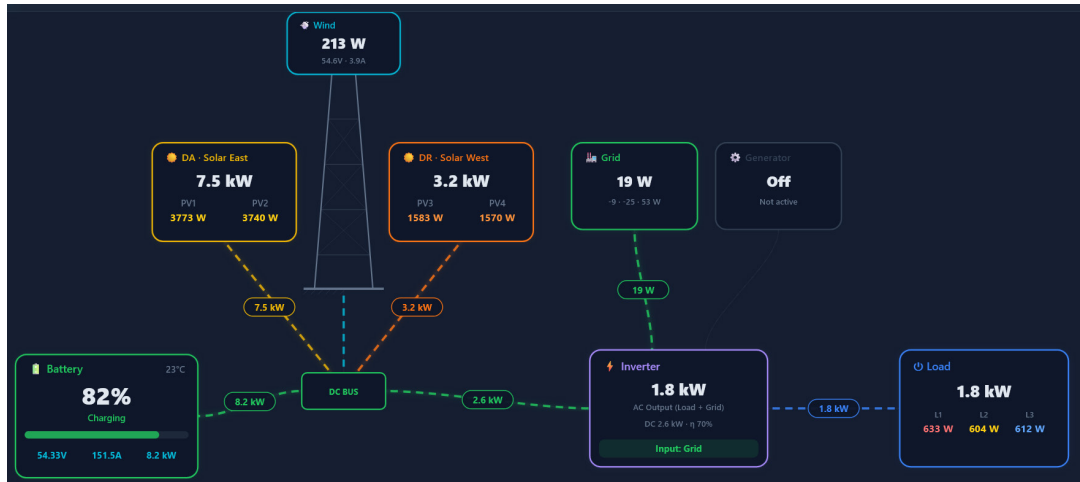


Fig. 12. Example of real-time energy flows and battery state of charge.

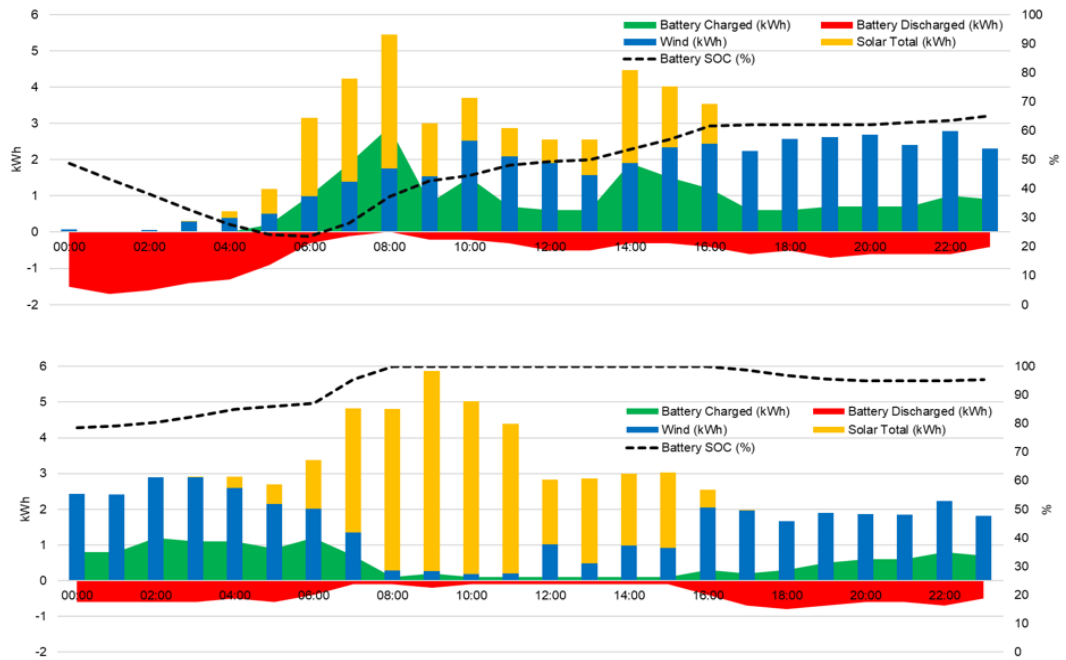


Fig. 13. Examples of 24-hours energy production and battery charging profiles in case of windy (top) and still conditions (bottom).

As shown, daily operation differs markedly – under windy conditions, sustained wind generation during night and evening hours limits battery discharge and maintains a high SOC, while daytime PV helps keep

the battery near full charge. Under low-wind conditions, the battery must cover a larger share of demand overnight, leading to a SOC decline, which is then partially reversed by PV-driven charging during daylight hours.

Week-scale example of power generation and battery state for the experimental tower (Fig. 14) highlights that autonomy is

primarily constrained by coincident low-irradiance and low-wind periods rather than by average renewable production.

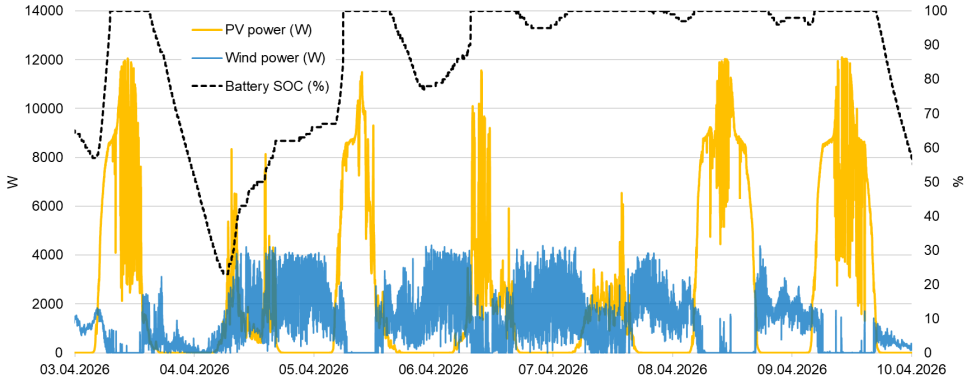


Fig. 14. Example of one-week renewable energy production and battery state of charge.

During cloudy and calm conditions, generation is insufficient to replenish storage and the battery SOC falls to ~20 % without recovering to full charge. With improved solar irradiance the following day, photovoltaic output increases and the SOC quickly return to 100 %, despite only moderate wind contribution. This behav-

iour indicates that achieving high uptime requires resilience against consecutive low-generation intervals, implying a need for additional storage, increased complementary generation (e.g., wind capacity), or backup/grid support to bridge worst-case events.

4. CONCLUSIONS

This study has presented a computational framework for optimising solar-wind-battery hybrid energy systems for low-power communication infrastructure under Latvian climatic conditions. The analysis has been carried out as a case study based on a real communication tower, modelling its performance using long-term meteorological data both at its specific location and across all of Latvia. The results show that reliable autonomous operation using only hybrid energy systems is achievable under Latvian conditions. To power a tower with an average consumption of 2.1 kW at 99 %

uptime, a system with costs ranging from roughly €38,000 to €55,000 is required. For the case study at a specific point in central Latvia, the lowest-cost configuration achieving 99 % uptime consisted of 36.7 kW of solar capacity, 5.9 kW of wind capacity, and 54 kWh of battery storage, totalling €45,678.

One of the main observations is the non-linear relationship between system cost and reliability. At lower cost levels, reliability improves quickly, but as uptime starts to approach the maximum, further improvements become increasingly costly. This

means that achieving maximal reliability using only intermittently available renewable energy resources can only be done with disproportionately large system sizes. The results also show that no single component should be optimised in isolation. The most cost-effective solutions require a balanced optimisation of the complementary available solar and wind power, alongside battery storage. Increasing only one component leads to inefficient systems with higher costs.

From a climatic perspective, wind energy has an especially important role in Latvia, especially during winter when solar generation is limited. Battery storage is essential for short-term balancing, but cannot compensate for extended periods of low generation, during which wind capacity becomes the key factor in maintaining system reliability.

It is important to note that the results of this study are based on a specific case with a defined set of assumptions, including component choices, cost parameters, and a fixed load profile. While the general trends observed are universal, exact numerical results should be interpreted with caution and only in the context of this particular

system.

The study shows that hybrid renewable energy systems can be a practical solution for powering low-demand autonomous infrastructure in Latvia, provided that system design is well balanced and adapted to local renewable energy availability and system-specific power consumption.

Future work should extend the current framework by incorporating additional factors that more closely align with real-world system performance and economic feasibility, such as component degradation over time, as well as considering the installation costs of energy systems. Similarly, system performance should be validated using real-world data to ensure the quality of the numerical model. Additionally, the inclusion of alternative system configurations, such as hybrid systems with backup generators or hydrogen storage, could help evaluate the potential to achieve near-100 % uptime at a balanced cost. Future studies could also expand the analysis to a broader geographical scope, including other Baltic or Northern European regions, to assess the universality of the observed trends under different climatic conditions.

ACKNOWLEDGEMENTS

The study has been supported by the Recovery and Resilience Mechanism the Research No. Z.1.3 “Development of a Prototype Hybrid Renewable Energy Gen-

eration and Smart Management System for Optimal Resource Utilization”, ID. No. 1.2.1.2.i.2/1/24/A/CFLA/008, MASOC KC support for green product development.

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