

Selection of energy storage capacity in a railway microgrid for island operation

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Abstract—This paper presents a methodology for optimizing the operation and sizing of a railway energy microgrid intended for island operation. The analyzed system integrates photovoltaic generation, battery energy storage, and traction substation load demand. The proposed model assumes that locally generated photovoltaic energy should primarily supply the traction load and charge the storage system, while energy export to the distribution grid is eliminated. A Particle Swarm Optimization algorithm is used to determine the required battery storage capacity under power balance, state-of-charge, depth-of-discharge and converter constraints. Simulations are performed for a traction substation using annual load data and photovoltaic generation profiles for south- and east-west-oriented panels. The results show a polynomial relationship between photovoltaic power and required storage capacity. For island operation, a one-hour autonomy criterion based on the P95 load level gives a storage capacity of 1437 kWh. State of Charge analysis confirms that this value covers most historical load windows, although extreme cases may still cause it to be violated.

Keywords—photovoltaic; battery energy storage; railway microgrid; island mode; Particle Swarm Optimization

I. INTRODUCTION

Trailway energy microgrid is a local power supply system for railway infrastructure, connecting a traction substation, non-traction loads, renewable energy sources, energy storage facilities and an energy flow control system. Its aim is to make more efficient use of energy, particularly energy from photovoltaic systems and energy recovered from regenerative braking of trains. The microgrid helps to reduce power consumption from the national electricity grid, lower energy costs and improve supply stability. In emergency situations, it can support the stand-alone operation of selected elements of the railway infrastructure, thereby increasing the resilience of the transport system.

A railway microgrid in island mode is a local power supply system for railway infrastructure that can operate temporarily independently of the external electricity grid. It typically comprises a traction substation, traction and non-traction loads, local power sources (e.g., photovoltaics), energy storage, and a control system. Island mode means that the microgrid is disconnected from the main grid but continues to supply power to selected loads. This is particularly important in emergency situations, such as power outages, damage to the distribution network, overloads, or external disturbances. This operating mode is intended to ensure continuous power supply to critical

components of the railway infrastructure. In practice, this may concern the power supply to railway traffic control equipment, telecommunications systems, lighting, safety equipment and selected traction requirements. In such a system, the storage facility acts as a buffer, stabilising the power balance and enabling demand to be met during periods when local generation is unavailable. Renewable energy sources, such as photovoltaic installations, can extend the microgrid's autonomous operating time and reduce the consumption of energy stored in the facility. The control system determines which loads take priority, how to utilise the energy storage facility, and when to reduce less critical loads. The use of a railway microgrid in island mode increases the resilience, reliability, and energy security of rail transport. In the scientific literature on this subject, a railway microgrid is defined as a local energy system that integrates renewable energy sources, energy storage systems, power electronic converters, traction and non-traction loads, and a central energy management system. Unlike conventional industrial or municipal microgrids, its operation is strongly determined by the variable traction load profile, short-term power peaks, regenerative braking energy, and the dependence of energy demand on the timetable and train speed profiles. In this literature, island mode is understood in two ways: as the technical capability to disconnect from the main grid whilst maintaining voltage and power stability, and as a mode of autonomous power supply to selected railway consumers, particularly critical and auxiliary infrastructure.

The starting point for the analysis is a review of works concerning energy storage and railway power supply architectures. The articles [1] and [2] organise energy storage system technologies, their functions in traction systems and operational limitations. In turn, article [3] illustrates the transition from conventional traction power supply to smart railway energy hub structures, in which management system, load forecasting and energy flow optimisation play a key role. This line of research is complemented by [4], which classifies AC, DC, and hybrid AC/DC architectures, identifying a common DC bus as the natural integration point for photovoltaic, energy storage, supercapacitors and regenerative braking energy.

The works most closely related to the issue of island operation concern the stability and control of DC microgrids. The article [5] proposes an architecture for a station-based DC microgrid integrating photovoltaics, a battery, a supercapacitor, and braking energy. A key point is that the system can operate both

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whilst connected to the AC grid and when disconnected from it, and DC voltage stability is formally analysed using non-linear methods. A similar technical approach is presented in [6], where the master Model Predictive Control sets power references for the PV, battery, and supercapacitor, which is crucial for microgrids designed for quasi-island operation. The second strand covers energy management in smart railway stations. The study presented in [7] employed a stochastic Mixed-Integer Linear Programming (MILP) model to optimize the utilization of photovoltaic generation, energy storage, and regenerative braking energy. The authors point out that the greatest benefits are derived from the use of photovoltaics, energy storage, and regenerative braking energy; however, island operation here functions more as local energy balancing than as a full emergency mode encompassing black start, protection selectivity, and traction autonomy. The publication [8] extends this issue to include the link between station microgrids and the train's power and speed profile, highlighting the need to close the loop between train movements and energy resource control. A direct comparison between standalone mode and grid-connected operation is presented in [9]. It demonstrates that standalone mode can supply part of a railway company's loads, whilst grid-connected mode may be more advantageous economically and environmentally, particularly with a higher share of photovoltaic. From the perspective of full island operation, however, this is more of a strategic analysis than a model of dynamic traction power supply. Similarly, the paper [10] introduces the concept of resilient, interconnected railway microgrids but does not yet address the long-term challenge of traction power supply posed by limited energy storage. A significant trend concerns photovoltaic and battery energy storage systems at traction substations. In the article [11], a railway system with photovoltaic, storage, and regenerative energy is modelled as an optimal power-flow problem. The paper [12] analyses a system comprising a photovoltaic system, battery storage, and a supercapacitor, highlighting the importance of hybrid storage for reducing costs and improving the utilisation of local energy. In contrast, [13] highlights the trade-off between photovoltaic self-consumption and the required energy storage capacity. In the Polish context, the paper [14] explores the problem of minimising energy export from a photovoltaic installation plus battery energy storage system at a traction substation. This is an important step towards operational autonomy, although it does not yet constitute a complete islanding model.

A separate group comprises studies on storage systems without photovoltaic, which are particularly important for the islanding variant based solely on a battery energy storage system. The study in [15] addresses the optimal placement and sizing of wayside energy storage systems, whereas [16] applies short-term load forecasting to reduce peak substation power demand. The paper [17] shows that the effectiveness of peak reduction depends on the capacity of the battery energy storage system, the permissible depth of discharge and the time required to recharge the storage system. These conclusions are directly relevant to island operation, as in autonomous mode, incorrect control of the battery energy storage can cause the minimum State of Charge to be reached prematurely. The most rapidly developing area is the integration of the management system

with train movements. In the article [18], it was demonstrated that the simultaneous optimisation of the speed profile and energy storage can reduce the demand for storage capacity. The publication [19] is a good counterpart to the stand-alone work, as the train operates with limited energy resources. In turn, [20] simultaneously optimises storage capacity, charge and discharge limits, the timetable, and driving style. Also important is the paper [21], which combines photovoltaic installation, timetable, speed trajectory and energy management system to create a methodological framework that can be extended to islanded conditions.

The review indicates that the literature provides a good description of energy storage systems, photovoltaic installations, energy management systems, peak shaving, and the optimisation of speed profiles, but still offers limited coverage of the full island operation of a high-power railway microgrid. The main research gap concerns the simultaneous consideration of energy balance without public grid support, State of Charge constraints, voltage stability, load prioritisation, power system protection, and the impact of train speeds and the timetable on the battery storage capacity requirement.

Our article [22] explores the problem of minimising energy export from a photovoltaic installation and battery storage system at a traction substation. This is an important step towards operational autonomy, although it does not yet constitute a complete islanding model. Microgrid operation was investigated based on the load profile of a railway traction substation in Poland, with Particle Swarm Optimization (PSO) applied to determine the optimal operating strategy.

In this article, we use a similar method but a different objective function. This article is focused on the operation of a railway microgrid in island mode. Using the Particle Swarm Optimization algorithm, the relationship between photovoltaic energy production and the maximum energy storage capacity was established, assuming zero energy export to the external grid. The time-domain load profiles of the analysed traction network were analysed, and on this basis, the energy storage capacity requirements for the operating conditions of the analysed railway microgrid in island mode were determined. The time-domain changes in State of Charge were also determined.

II. RAILWAY MICROGRID MODELING

Figure 1 illustrates the architecture of the railway energy microgrid considered in this study, consisting of a photovoltaic installation and a battery energy storage system. The photovoltaic system is connected to the battery energy storage system, the distribution grid, and the traction substation. The generated photovoltaic energy is primarily used to supply the traction substation, with any surplus used to charge the battery energy storage system. It is assumed that no electricity generated by the photovoltaic panels is exported to the grid. As a result, the energy storage is fully charged by the photovoltaic system. To satisfy this requirement, the battery storage capacity is assumed to be sufficiently large. When photovoltaic generation is insufficient to meet the load demand, the energy storage system supplies the deficit, with any remaining power demand covered by the external grid.

linked to the balance between photovoltaic generation, traction demand, and power transferred outside the local system.

III. OPTIMIZATION FRAMEWORK FOR PHOTOVOLTAIC – BATTERY ENERGY STORAGE OPERATION

Particle Swarm Optimization (PSO) was selected as the numerical method for solving the formulated optimization problem. The algorithm is widely applied to optimization tasks because it can handle different objective-function formulations, constraint sets, and solution-space dimensions. Its applicability to optimization problems in power systems has also been demonstrated in previous studies [22, 25]. Among population-based evolutionary techniques, PSO is particularly attractive for its relatively simple implementation, satisfactory convergence properties, and limited sensitivity to the choice of initial solutions [26–29]. The optimization procedure is governed primarily by the inertia coefficient, the cognitive coefficient, and the social coefficient. The inertia coefficient determines how strongly a particle preserves its previous motion, whereas the cognitive coefficient controls the influence of the particle's own experience. In turn, the social coefficient determines the contribution of the best solution identified by the swarm. For the calculations performed in this study, the swarm consisted of 50 particles and the maximum number of generations was set to 100. The remaining PSO parameters were set to the inertia coefficient 0.5, the cognitive coefficient 2, and the social coefficient 2. To reduce the influence of the stochastic nature of the algorithm and improve the likelihood of identifying the global optimum, the optimization procedure was repeated independently 10 times. The optimization problem was formulated to maximize the battery energy storage capacity for a specified level of photovoltaic generation while ensuring that the traction substation is supplied with the required power. In addition, the model assumes that surplus energy is not exported to the external grid. The feasible solution space is therefore defined by the following constraints:

$$0 \leq P_{pv}(t) \leq P_{pv,max}, \quad (7)$$

$$P_{b,in,1}(t) \geq 0, \quad (8)$$

$$P_{b,out,1}(t) \leq P_{b,max}, \quad (9)$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max}, \quad (10)$$

$$P_b(t) + P_{pv}(t) \geq P_{load}(t). \quad (11)$$

Constraint (7) defines the permissible power range of the photovoltaic installation. Constraints (8) and (9) specify the battery energy storage system's operating power limits. The allowable battery state-of-charge and discharge conditions are imposed by constraint (10), while constraint (11) ensures that the power balance is satisfied at each time step considered.

IV. RESULTS OF THE SIMULATION OF A RAILWAY MICROGRID

A. Input dataset

The numerical analysis was performed for the Garbce Żmigród traction substation, located at (51°30'47"N 16°53'03"E). Input data includes environmental conditions affecting the operation of the photovoltaic installation, technical parameters

of the photovoltaic installation and battery energy storage, and load on the traction substation and limit energy. The study covered the entire year 2024 and incorporated both the traction substation's electricity demand and the environmental conditions governing photovoltaic generation. The traction load profiles were obtained from PGE Energetyka Kolejowa's central measurement data repository and correspond to the operation of the Garbce Żmigród facility throughout 2024 [22]. Meteorological inputs describing solar irradiation and ambient temperature over the same period were obtained from source [30]. The model input dataset, therefore, combines three main groups of information: the traction substation load, the operating conditions of the photovoltaic installation, and the technical characteristics of both the photovoltaic source and the battery energy storage system. An additional energy limit was included among the input quantities that define the calculation framework. The photovoltaic subsystem was represented using a module efficiency (η_{pv}) of 90% and a rated power ($P_r(pv)$) of 10 kW. Standard Test Conditions were defined using an irradiance level (N_{stc}) of 1 kW/m² and a reference cell temperature (T_{stc}) of 25 °C. The influence of temperature on photovoltaic performance was taken into account through a temperature derating coefficient (γ) of 0.5 % W/°C. The Normal Operating Cell Temperature (NOCT) was assumed to be 45 °C. The battery energy storage model was parameterized using charging and discharging efficiencies of 95%, denoted respectively by $\eta_{b,in}$ and $\eta_{b,out}$. The initial SOC was set to 75%, with minimum and maximum admissible values of 20% and 100%, respectively. In addition, the maximum DOD was limited to 80%. By combining the annual traction-demand data with the corresponding 2024 irradiation and temperature profiles, the adopted dataset provides a consistent basis for evaluating interactions among photovoltaic generation, battery storage operation, and the traction substation's electrical demand.

B. Simulation results

Figure 4 shows the variation in the maximum energy storage capacity (CoS) as a function of the value of the photovoltaic installation (P_{pv}). for DOD=80% and a south orientation of the photovoltaic installation.

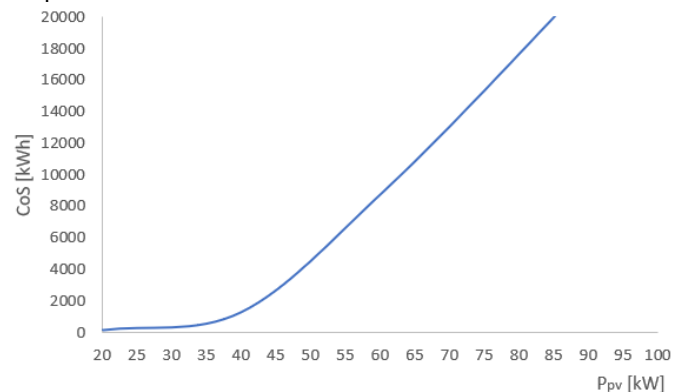


Fig. 4. Relationship between the maximum energy storage capacity and value of the photovoltaic installation for DOD=80 % and south orientation of the photovoltaic installation

Figure 5 shows the same relationship for the east-west orientation of the photovoltaic installation.

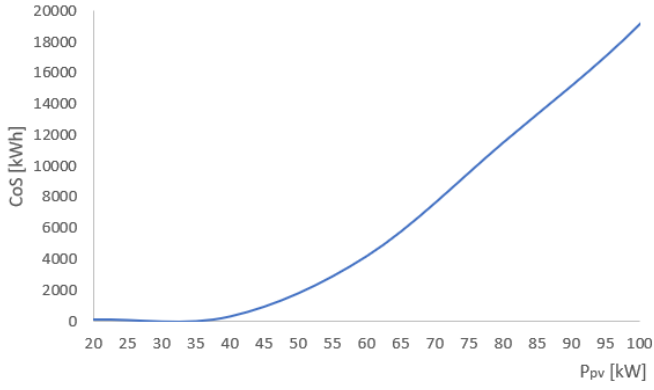


Fig. 5. Relationship between the maximum energy storage capacity and value of the photovoltaic installation for DOD=80 % and east-west orientation of the photovoltaic installation

The correlation depicted in Fig. 4 can be formulated using the following equation:

$$CoS = 1.8003P_{pv}^2 + 141.434P_{pv} - 5224.09, \quad (12)$$

with R-squared coefficient 0.9968.

In turn, the relationship presented in Fig. 5 is described by the following equation:

$$CoS = 4.2018P_{pv}^2 - 274.126P_{pv} + 4641.14, \quad (13)$$

with R-squared coefficient 0.9962.

V. ANALYSIS OF THE OPERATION OF AN ISLAND MICROGRID

A. Determining the required battery energy storage capacity

In island mode, the power supply for the traction substation of the analyzed railway microgrid comes exclusively from the battery energy storage; no power is imported from the grid. We are assuming the worst-case scenario, namely that the photovoltaic panel system is not generating any energy. For the analysis, it was assumed that the island operation time is 1 hour. An island operation time of 1 hour was adopted as the representative emergency autonomy time for a railway microgrid. This period is sufficient to maintain traction power supply during a short-term disruption, perform switching procedures, reduce the load, or safely terminate train operations on the supplied section. At the same time, the 1-hour horizon limits the risk of oversizing the energy storage system, which would occur if a longer autonomy time were assumed. Therefore, the adopted assumption represents a compromise between the system's operational resilience and the technical and economic rationality of selecting storage capacity. Figure 6 presents load histogram.

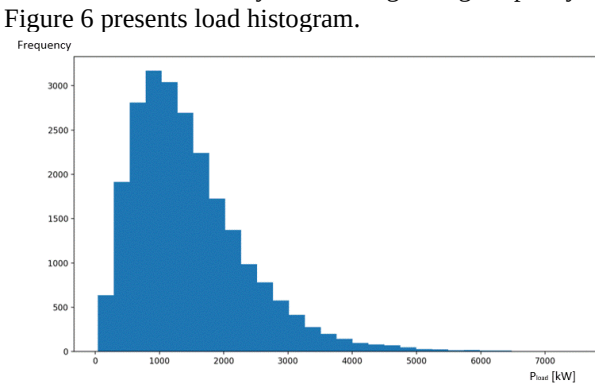


Fig. 6. Load histogram for the year 2024 (Garbce Zmigrod traction substation)

The histogram is based on year-round measurements of the traction substation's load taken at 15-minute intervals. The load profile of the traction substation was analyzed based on a 1-hour time window. The time window was shifted by 15 minutes.

Our goal is to provide 1 hour of off-grid (island mode) power without recharging the battery energy storage system. Based on this assumption, we will determine its capacity. The energy storage capacity was determined at the P95 (95th percentile). This choice represents a compromise between technical safety and the system's capital cost. Furthermore, it serves as a good measure of the system's design resilience to typical high loads, without fully oversizing it for the rarest extreme cases.

The relationship describing the required energy storage capacity (CoS) can be expressed using the following equation:

$$CoS = \frac{E_{1h}}{\eta_{bat,out}(SoC_{max} - SoC_{min})} \cdot \frac{1 + MAR}{f_{EOL}}. \quad (14)$$

Where E_{1h} is energy required during a one-hour period (energy for the P95 reliability level), $\eta_{b,out}$ is efficiency associated with discharging battery energy storage, SoC_{max} is maximum SOC, SoC_{min} is minimum SOC, MAR is safety margin, f_{EOL} is End-of-Life factor.

For our calculations, we used the following values:

E_{1h} : 794,2 kWh,

$\eta_{b,out}$: 95 %,

SoC_{max} : 100 %,

SoC_{min} : 20 %,

MAR: 10 %,

f_{EOL} : 80 %.

We obtained a CoS value of 1437 kWh.

For the south-oriented photovoltaic installation and equation (12), we obtain $P_{pv} = 33.13$ kW. On the other hand, for equation (13), i.e., for an east-west orientation of the photovoltaic installation, we obtain $P_{pv} = 49.98$ kW.

B. Analysis of changes in the SoC of battery energy storage

The analysis of changes in the battery energy storage system's SOC was conducted hourly, with 15-minute intervals. It allows us to determine whether the battery energy storage system falls below SoC_{min} , how often this occurs, during which hours of the day the problem is most severe, the number and depth of cycles, and whether different times of day carry different risks of the storage system running out.

The process of discharging the battery energy storage can be described using an equation that describes the change in the energy stored within it:

$$E(k+1) = E(k) - \frac{P_{load}\Delta t}{\eta_{b,out}}. \quad (15)$$

Where: $P_{load}(k)$ denotes the traction load at time k , $\Delta t = 0.25$ h for samples taken every 15 minutes.

The equivalent of the (18) relationship is an expression describing the change in SoC:

$$SoC(k+1) = SoC(k) - \frac{P_{load}\Delta t}{\eta_{b,out}CoS_{nom}}. \quad (16)$$

Where $SoC(k)$ denotes SoC at time k , CoS_{nom} is the nominal energy capacity of the battery energy storage. The value of CoS_{nom} is 1437.0 kWh.

Based on an analysis of SOC changes relating to the load on the traction substation in question (namely the Garbce-Zmigrod traction substation throughout 2024), it was established that:

1. The storage system falls below SoC_{min} in 1.19% of hourly time windows, on average, about once every 84-time windows.

2. The highest risk occurs primarily between 3:00 p.m. and 6:45 p.m. (24.6% share), followed by approximately 8:00 p.m. to 8:45 p.m. (4.5% share), and there is also a noticeable period of elevated risk at night between approximately 3:00 a.m. and 3:45 a.m. (3.6% share).
3. In most cases, critical discharge occurs only toward the end of the hour.
4. A capacity of 1437 kWh is sufficient for most time windows but does not fully cover all analyzed load cases.
5. The worst-case scenario is a load energy of 1867.7 kWh in an hourly window. This results in the energy required from the storage system, after accounting for efficiency, being 1966.0 kWh. This implies a calculated $\text{SoC}_{\min}$ of -36.8% . A negative SOC result has no physical meaning; it merely indicates that our designed storage system would not be able to cover this window even if starting from 100% SOC.

CONCLUSION

The study presented a methodology for optimizing the operation and sizing of a railway energy microgrid composed of a photovoltaic installation and battery energy storage. The proposed approach combines a physical model of photovoltaic generation, traction substation load demand, battery state-of-charge constraints, and Particle Swarm Optimization to determine the required storage capacity under the assumption of eliminating energy export to the distribution grid. This assumption is particularly important for railway microgrids, where locally generated renewable energy should primarily support traction power supply and improve the system's self-consumption. The simulation results confirmed that battery energy storage capacity strongly depends on the installed photovoltaic power and the orientation of photovoltaic panels. Both south-oriented and east-west-oriented photovoltaic installation configurations showed a high-quality polynomial relationship between photovoltaic system power and required storage capacity, with very high coefficients of determination. This indicates that the proposed modelling approach can be used at the design stage to estimate the required storage scale for different photovoltaic installation configurations and operational assumptions. The analysis of island operation demonstrated that a one-hour autonomy period represents a practical compromise between operational resilience and economic rationality. For the analyzed Garbce-Żmigród traction substation, the storage capacity calculated for the P95 load criterion was 1437.0 kWh. This value ensures coverage of most historical one-hour load windows, but it does not guarantee full coverage of all extreme cases. The SOC analysis showed that the storage system falls below the minimum SOC threshold in 1.19% of hourly windows, primarily during the afternoon and evening periods with increased traction load. The worst-case load window would require significantly greater storage capacity, confirming that full coverage of all historical cases may lead to substantial oversizing. Therefore, the obtained results show that the proposed method provides a useful engineering tool for selecting battery storage capacity in railway microgrids. It enables a balanced design between renewable energy utilization, island-operation capability, system resilience, and investment cost.

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