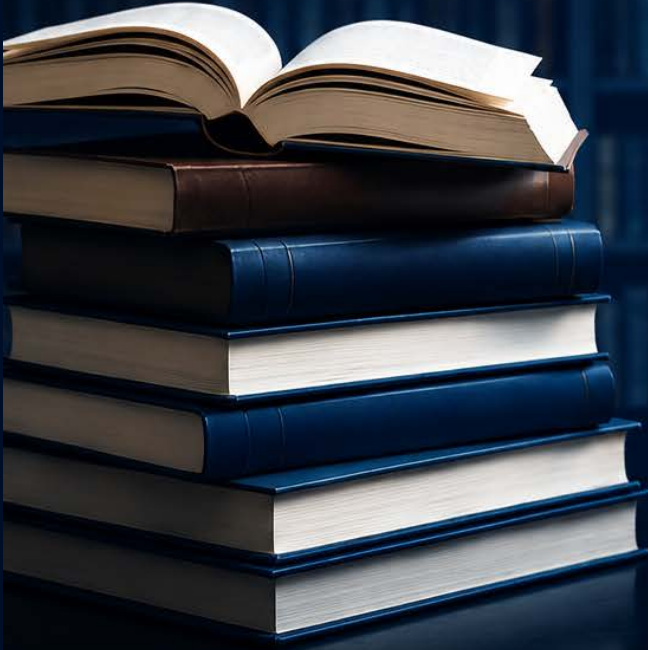


ENERJİ SİSTEMLERİ MÜHENDİSLİĞİ ALANINDA GÜNCEL KONULAR VE AKADEMİK DEĞERLENDİRMELER

Editör: Doç.Dr. Aslıhan KURNUÇ SEYHAN



yaz
yayınları

**Enerji Sistemleri Mühendisliği Alanında
Güncel Konular ve Akademik Değerlendirmeler**

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İÇİNDEKİLER

Optimization of Distributed Energy Resources and Power Flow Analysis in Virtual Power Plants.....	1
<i>Burkan Alp KALE, Sıtkı KOCAOĞLU, Tuba ÇAĞLIKANTAR</i>	
Multi-Barrier Geological Disposal Design for Spent Nuclear Fuel from Small Modular Reactors Using Domestic Mineral Resources	22
<i>Emine KÜÇÜKYAVUZ, Furkan UZUN, Tuba ÇAĞLIKANTAR, Sıtkı KOCAOĞLU</i>	
Equipment Selection, Sizing, and System Integration in Biogas Plants.....	42
<i>Durmuş TEMİZ, Ali AKYÜZ, Kazım KUMAŞ, Mustafa AYAN</i>	

"Bu kitapta yer alan bölümlerde kullanılan kaynakların, görüşlerin, bulguların, sonuçların, tablo, şekil, resim ve her türlü içeriğin sorumluluğu yazar veya yazarlarına ait olup ulusal ve uluslararası telif haklarına konu olabilecek mali ve hukuki sorumluluk da yazarlara aittir."

OPTIMIZATION OF DISTRIBUTED ENERGY RESOURCES AND POWER FLOW ANALYSIS IN VIRTUAL POWER PLANTS

Burkan Alp KALE¹

Sıtkı KOCAOĞLU²

Tuba ÇAĞLIKANTAR³

1. INTRODUCTION

The increasing penetration of renewable energy sources and distributed energy resources (DERs) is transforming the structure and operation of modern electrical power systems. Conventional power systems have traditionally relied on large centralized generation units supplying electricity to consumers through transmission and distribution networks. However, the widespread deployment of photovoltaic (PV) systems, wind turbines, battery energy storage systems (BESSs), combined heat and power (CHP) units, electric vehicles (EVs), and flexible loads has resulted in a more decentralized and dynamic energy landscape. Although these resources can contribute to decarbonization, energy efficiency, and supply flexibility, their distributed nature and variable operating characteristics introduce significant challenges for coordinated power system operation.

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The virtual power plant (VPP) concept has emerged as an effective framework for addressing these challenges. A VPP aggregates geographically distributed generation, storage, and controllable demand resources and coordinates them as a unified energy portfolio. Through aggregation and centralized or hierarchical energy management, relatively small DERs can collectively participate in energy management and market-oriented operations while supporting the balance between electricity generation and consumption. Consequently, the operational performance of a VPP depends not only on the installed capacities of its constituent resources but also on the dispatch and optimization strategies used to coordinate them.

Energy management within a VPP constitutes a constrained, time-dependent optimization problem. At each time interval, electricity demand must be balanced with renewable generation, storage operation, and power exchanged with the utility grid. The presence of energy storage makes this problem inherently intertemporal because charging or discharging decisions made at one time step influence the energy available during subsequent periods. Renewable generation uncertainty, variations in electricity demand, market prices, battery state of charge (SOC), charging and discharging limits, and grid exchange constraints further increase the complexity of the dispatch problem. Therefore, optimization approaches such as mixed-integer linear programming (MILP) and model predictive control (MPC), together with simpler rule-based strategies, provide important tools for evaluating alternative VPP operating policies.

Economic optimization alone, however, is not sufficient to characterize the operation of a VPP connected to an electrical distribution network (Martin & Hiskens, 2016). Dispatch decisions determine the active power injections and withdrawals throughout the system and may consequently affect bus voltages,

branch loading, and network losses. Integrating energy-management optimization with power-flow analysis therefore provides a more comprehensive framework in which both economic operation and electrical network behavior can be examined (Talukder, 2026). This integration is particularly valuable for planning studies and comparative analyses involving different combinations of renewable generation, storage, and flexible resources.

This chapter presents an integrated approach to the optimization and power-flow analysis of DERs within a VPP framework. The discussion covers the fundamental structure of VPPs, the representation of distributed generation and storage resources, energy-management and dispatch formulations, and alternative optimization strategies. A computational case study based on VPPsim Pro, a visual VPP simulation environment, is subsequently used to demonstrate the proposed framework. The case study combines PV generation, wind generation, battery storage, CHP resources, load profiles, electricity-market data, and grid exchange within a 24-hour operational horizon. Dispatch is evaluated using alternative control approaches, including MILP-based optimization, while network behavior is examined through GridLAB-D-based power-flow analysis.

The objective of the chapter is therefore not to propose a new optimization algorithm, but to demonstrate how DER aggregation, dispatch optimization, energy storage management, and distribution power-flow analysis can be incorporated into a coherent and reproducible VPP analysis framework. Particular attention is given to the relationships among renewable energy utilization, battery operation, grid imports and exports, operating cost, and network constraints. The resulting framework provides a basis for investigating different VPP configurations and operating scenarios and for identifying opportunities for more

advanced optimization, forecasting, and network-aware energy-management approaches.

2. VIRTUAL POWER PLANTS AND DISTRIBUTED ENERGY RESOURCES

2.1. Virtual Power Plant Concept

A Virtual Power Plant (VPP) is an aggregated energy management structure that coordinates geographically distributed generation, storage, controllable loads, and grid interaction through a common control framework (Liu, Hu, Yu, & Trinh, 2023). Rather than operating each distributed energy resource (DER) independently, a VPP manages the portfolio as a coordinated system according to technical and economic objectives (Marinescu et al., 2022).

The main function of a VPP is to balance generation and demand while considering renewable availability, storage constraints, electricity prices, and grid Exchange (Ullah, Mokryani, Campean, & Hu, 2019). This coordinated structure enables distributed resources to contribute to energy management, peak reduction, renewable energy utilization, and market-oriented operation. In this chapter, the VPP is considered primarily as an optimization-based aggregation framework in which the operating schedules of individual resources are determined over a defined time horizon.

2.2. Distributed Generation Resources

Renewable generation represents an important component of the VPP considered in this study. Solar PV and wind generation are characterized by variable and weather-dependent output, creating a temporal mismatch between generation and electricity demand. Their coordinated operation with storage and grid

exchange is therefore essential for maintaining the energy balance.

For the optimization problem, PV and wind generation are represented by time-dependent power profiles. The available renewable power at each time step contributes directly to meeting electrical demand, while any remaining imbalance is compensated by battery operation or grid exchange. This representation allows the effects of renewable variability to be incorporated into the dispatch problem without requiring detailed component-level models.

2.3. Battery Energy Storage

Battery energy storage provides temporal flexibility by transferring energy between different operating periods (Li et al., 2015). During charging, electrical energy is stored for later use, whereas during discharging the stored energy can reduce grid imports or support local demand. Battery operation is constrained by rated charging and discharging power, energy capacity, charging and discharging efficiencies, and allowable state-of-charge (SOC) limits.

Within a VPP, battery scheduling can be driven by both technical and economic considerations (Kanakadhurga, Chandrakala, Sanjari, & Shareef, 2026). Charging may be preferred during periods of high renewable generation or low electricity prices, while discharging may be advantageous during high-demand or high-price periods. Consequently, battery storage introduces an intertemporal dimension into the VPP optimization problem because a charging or discharging decision at one time step affects the available energy in subsequent periods.

2.4. Controllable and Flexible Resources

In addition to renewable generation and battery storage, a VPP may incorporate controllable resources such as combined

heat and power (CHP) units, electric vehicles, heat pumps, and flexible electrical loads (Wang et al., 2019). These resources increase operational flexibility by allowing generation or consumption to be adjusted according to system requirements.

The case-study environment considered in this chapter supports several such resource categories. However, not all configured assets are represented as independent decision variables in the current aggregate dispatch formulation. In particular, the CHP unit is included in the VPP configuration and network-related data but is not independently scheduled within the main dispatch decision vector. This distinction is important when interpreting the optimization results.

2.5. Grid Interaction and Energy Balance

The external grid provides the balancing interface between the VPP and the wider electricity system (Pudjianto, Ramsay, & Strbac, 2007). When local renewable generation and battery discharge are insufficient to meet demand, energy can be imported from the grid. Conversely, excess energy can be exported when local generation exceeds consumption and storage requirements.

The resulting energy balance depends on the interaction among renewable generation, demand, battery operation, and grid exchange. Electricity prices provide an additional economic signal that influences the timing of imports, exports, charging, and discharging. Therefore, coordinated management of these resources forms the basis of the optimization problem developed in the following section.

3. ENERGY MANAGEMENT AND OPTIMIZATION IN VIRTUAL POWER PLANTS

3.1. Energy Management Problem

The energy management system is the operational core of a VPP because it determines how available generation, storage, demand, and grid exchange should be coordinated over time. At each time interval, the controller must ensure that electrical demand is satisfied while respecting the technical limitations of individual resources. Since renewable generation, electricity demand, and market prices vary throughout the day, the preferred operating decision may also change from one period to another.

The dispatch problem becomes particularly important when battery energy storage is included (Teleke, Baran, Bhattacharya, & Huang, 2010). A battery can shift electrical energy between different periods, but its available energy is limited by its capacity and SOC (Meissner & Richter, 2003). Consequently, a charging or discharging decision made at one hour affects the feasible operating decisions during subsequent hours. The energy management problem must therefore be formulated over a time horizon rather than solved as a set of completely independent instantaneous power balances.

In the considered framework, the principal variables involved in dispatch are PV generation, wind generation, electrical load, battery charging and discharging, and power imported from or exported to the utility grid. The optimization is performed over 24 one-hour intervals. This formulation enables the system to coordinate renewable generation and battery operation while considering variations in demand and electricity price throughout the day.

3.2. Power Balance

The fundamental physical requirement of the dispatch model is the electrical power balance (Yang, Yong, & Xiang, 2023). For each time interval (t), the total power supplied by renewable generation, battery discharge, and grid import must equal electrical demand together with battery charging and grid export. The power balance can be expressed as:

$$P_{load,t} + P_{ch,t} = PPV,t + P_{wind,t} + P_{dis,t} + P_{imp,t} - P_{exp,t} \quad (1)$$

where $P_{load,t}$ is the electrical load, PPV,t and $P_{wind,t}$ are the available PV and wind powers, $P_{ch,t}$ and $P_{dis,t}$ denote battery charging and discharging power, and $P_{imp,t}$ and $P_{exp,t}$ represent grid import and export, respectively.

This relationship must be satisfied at every simulation interval. If renewable generation is lower than demand, the resulting deficit can be supplied by battery discharge, grid import, or a combination of both. When renewable generation exceeds demand, the surplus can be directed to battery charging or grid export according to the operating constraints and optimization objective.

3.3. Battery State-of-Charge Model

Battery operation introduces a dynamic relationship between consecutive time intervals (Maheshwari, Paterakis, Santarelli, & Gibescu, 2020). The SOC at the current time depends on the previous SOC together with the energy charged into or discharged from the battery. For the one-hour time intervals considered in this study, the SOC relationship is represented as:

$$SOC_t = SOC_{t-1} + (\eta_{ch} P_{ch,t} / E_{bat}) - (P_{dis,t} / \eta_{dis} E_{bat}) \quad (2)$$

where E_{bat} is the battery energy capacity and η_{ch} and η_{dis} are the charging and discharging efficiencies, respectively. The

implemented model derives these efficiencies from the specified round-trip efficiency by assigning:

$$\eta_{ch} = \eta_{dis} = \sqrt{\eta_{round-trip}} \quad (3)$$

Battery operation is further restricted by minimum and maximum SOC values:

$$SOC_{min} \leq SOC_t \leq SOC_{max} \quad (4)$$

and by maximum charging and discharging power:

$$0 \leq P_{ch,t} \leq P_{ch,max} \quad (5)$$

$$0 \leq P_{dis,t} \leq P_{dis,max} \quad (6)$$

3.4. Objective Function

The optimization objective is formulated to minimize the total operating cost over the considered time horizon. The principal economic contribution is associated with electricity imported from or exported to the external grid. Battery operation can additionally be assigned a degradation-related cost to discourage unnecessary cycling. The objective function is expressed as:

$$\min \sum_t [c_t(P_{imp,t} - P_{exp,t}) + c_{deg}(P_{ch,t} + P_{dis,t})] \quad (7)$$

where c_t represents the electricity price at time t , and c_{deg} represents the battery degradation cost associated with charging and discharging throughput.

3.5. Mixed-Integer Linear Programming Formulation

Mixed-integer linear programming is used as the principal optimization method in the computational case study. The backend MILP formulation contains seven variable groups for each hour: battery charging power, battery discharging power, binary charging state, binary discharging state, grid import, grid export, and battery SOC.

Binary variables are introduced to represent mutually exclusive battery operating states. Big-M constraints link the charging and discharging powers to their corresponding binary variables, while an additional mutual-exclusion constraint prevents the battery from charging and discharging simultaneously. This formulation allows operational logic to be incorporated while retaining a linear objective function and linear system constraints.

4. CASE STUDY: VPPSIM PRO

4.1. System Overview

VPPsim Pro is a computational simulation environment developed to integrate VPP configuration, energy management optimization, and power-flow analysis within a common framework. The system enables different distributed energy resources to be represented as interconnected components and converts the configured VPP structure into the input data required for dispatch optimization and network analysis. The platform was designed primarily for planning, comparative analysis, and research-oriented simulations rather than real-time control of physical energy systems.

The computational architecture consists of four main functional layers. The first layer provides the visual representation and configuration of DERs. The second layer converts the configured system into structured optimization and power-flow inputs. The third layer performs energy dispatch using either browser-based algorithms or a local optimization backend. The fourth layer processes simulation outputs and provides operational indicators including renewable generation, battery power, SOC, grid exchange, operating cost, bus voltage, branch loading, and network losses.

4.2. Reference VPP Configuration

A reference VPP configuration was used to demonstrate the interaction among renewable generation, energy storage, electricity demand, and the utility grid. The configuration combines solar PV generation, wind generation, battery storage, and a biomass CHP unit. The external power grid provides the balancing interface, while the control structure represents the coordination of the aggregated resources.

The main parameters of the reference configuration are summarized in Table 1.

Table 1. Main Parameters of the Reference VPP Configuration

Resource	Rated Capacity	Main Operating Parameters
Solar PV	3.6 MW	21% efficiency, 28° tilt, 180° azimuth
Wind Farm	4.2 MW	3.2 m/s cut-in, 11.5 m/s rated, 24 m/s cut-out
Battery Storage	2.4 MW / 9.6 MWh	92% round-trip efficiency, 12–92% SOC, 52% initial SOC
Biomass CHP	2.2 MW electric / 3.4 MW thermal	36% electrical efficiency, 48% thermal efficiency
External Grid	100 MW software limit	Import/export balancing interface

4.3. Simulation Profiles and Operational Horizon

The VPP is evaluated over a 24-hour simulation horizon using one-hour time intervals. For each interval, the dispatch model processes renewable generation, electrical demand, market price, battery state, and grid exchange. The selected horizon is sufficiently long to represent the daily variation of solar generation, wind generation, demand, and electricity prices while also capturing the intertemporal behavior of battery storage.

PV and wind generation are represented by time-dependent generation profiles scaled according to their installed capacities. The electrical demand is represented through predefined load profiles, while the electricity market is

characterized by hourly price data. The simulation environment supports different weather, demand, and market conditions, enabling the same VPP architecture to be evaluated under alternative operating scenarios.

For reproducible evaluation, the simulation profiles used in the case study are generated using fixed random seeds. This approach ensures that repeated simulations use identical renewable generation, load, and market conditions. Consequently, differences between simulation results can be attributed to the VPP configuration or dispatch strategy rather than uncontrolled variations in input profiles.

4.4. Dispatch and Power-Flow Analysis

The case study combines energy dispatch optimization with distribution power-flow analysis. The dispatch stage determines the hourly operation of the battery and the exchange of electrical energy with the utility grid while satisfying the power-balance and SOC constraints defined in Section 3. The MILP formulation is used as the principal optimization approach for the controlled scenario comparison.

Following the dispatch analysis, the electrical topology can be transferred to GridLAB-D for power-flow calculation. The implemented network representation uses 12.47 kV nodes and distribution lines with default electrical parameters. The power-flow stage provides bus voltage, branch loading, and network loss information, thereby complementing the economic and energy-management results obtained from the dispatch optimization.

The current power-flow implementation is intended primarily as a network convergence and integration analysis rather than a fully validated distribution-feeder model. It uses a snapshot representation and predefined line parameters. Therefore, its results are used to examine the operation of the integrated simulation workflow and basic network behavior

rather than to make detailed conclusions regarding hosting capacity or real distribution-system performance.

5. RESULTS AND DISCUSSION

5.1. Dispatch Optimization Results

The operational performance of the VPP configurations was evaluated over a 24-hour horizon using the MILP dispatch model. Four scenarios, namely Reference VPP, Campus Peak, Wind Firming, and Microgrid, were analyzed using the same optimization approach. This enables differences in system performance to be associated primarily with variations in installed capacities, renewable generation profiles, electrical demand, storage characteristics, and market conditions.

The principal results of the four scenarios are summarized in Table 2.

Table 2. MILP-Based Comparison of the VPP Scenarios

Scenario	Renewable Utilization (%)	Battery Throughput (MWh)	Net Grid Import (MWh)	Net Grid Export (MWh)	Net Operating Cost (\$)
Reference VPP	100.00	12.90	78.62	0.15	8,138.38
Campus Peak	92.31	1.82	20.24	3.35	817.47
Wind Firming	99.37	6.97	36.02	2.46	3,007.07
Microgrid	95.99	0.00	8.25	0.64	340.37

5.2. Hourly Operation of the Reference VPP

The hourly dispatch results of the Reference VPP provide further insight into the interaction between renewable generation, battery storage, electricity demand, and market prices. The battery begins the simulation with an SOC of 52%. During hour 2, the optimization model charges the battery at 2.40 MW,

increasing the SOC to 76%. This charging action occurs when the electricity price is relatively low at \$35.3/MWh.

During periods of higher electricity prices, stored energy is used to reduce grid imports. At hour 9, for example, the battery discharges at its maximum rate of 2.40 MW while the market price reaches \$169.9/MWh. The SOC consequently decreases from 64.1% to 38.1%. At hour 11, the battery again discharges at 2.40 MW when the electricity price reaches \$176.7/MWh, reducing the SOC to its minimum permitted level of 12%.

The battery is subsequently recharged at hour 16, when the market price decreases to \$32.0/MWh. Charging at 2.40 MW increases the SOC from 12% to 36%. At hour 17, when the electricity price rises to \$157.5/MWh, the battery discharges 2.21 MW and returns to the minimum SOC level. At this time, renewable generation and battery discharge are sufficient to eliminate grid import and produce a small grid export of 0.15 MW.

These results illustrate the intertemporal behavior of the MILP dispatch formulation. Battery operation is not determined solely by instantaneous renewable surplus or electricity demand. Instead, the optimization algorithm considers the electricity-price profile together with future system requirements and battery constraints. The resulting schedule therefore shifts battery charging toward relatively low-price periods and discharging toward relatively high-price periods.

5.3. Power-Flow Results

Power-flow calculations were performed for all four VPP configurations using the GridLAB-D simulation path. All evaluated network models converged successfully. The minimum calculated bus voltages remained close to 1.0 pu, while the maximum branch loading among all scenarios was 27.02%. The corresponding results are summarized in Table 3.

Table 3. GridLAB-D Power-Flow Results

Scenario	Buses	Branches	Minimum Voltage (pu)	Maximum Loading (%)	Losses (MW)	Converged
Reference VPP	4	3	0.99956	24.01	0.001070	Yes
Campus Peak	5	4	0.99935	27.02	0.001571	Yes
Wind Firming	4	3	0.99972	15.00	0.000420	Yes
Microgrid	5	4	0.99972	11.50	0.000273	Yes

These power-flow results should be interpreted within the limitations of the implemented network model. The present GridLAB-D configuration is a snapshot analysis using predefined line parameters rather than a validated time-series representation of an actual distribution feeder. Furthermore, configured generation is retained in the power-flow request metadata, while explicit generator injection objects are not yet represented in the current GridLAB-D model. Consequently, the results primarily demonstrate successful topology generation, numerical convergence, and data exchange between the optimization and power-flow components rather than validation of the electrical performance of a real distribution network.

5.4. Discussion

The scenario results demonstrate that the operational behavior of a VPP is strongly influenced by the combination of resource capacity, load profile, market conditions, and battery constraints. High renewable penetration does not necessarily eliminate dependence on the utility grid because the temporal distribution of renewable generation may differ substantially from the demand profile. Energy storage can reduce this temporal mismatch, but its operation depends on both technical limitations and the economic signals incorporated into the optimization objective.

The Reference VPP provides a clear example of price-responsive battery operation. The MILP model charges the battery during relatively low-price periods and discharges during high-price periods while maintaining the specified SOC limits. In contrast, the Microgrid scenario demonstrates that storage operation is not inherently beneficial under every set of conditions. With a flat electricity-price profile and an explicit battery degradation cost, the optimizer identifies no economic incentive for battery cycling.

6. CONCLUSION

The increasing integration of distributed renewable generation, energy storage, and flexible energy resources requires coordinated energy management approaches capable of considering both economic objectives and technical operating constraints. Virtual power plants provide an appropriate framework for this purpose by aggregating heterogeneous distributed energy resources and coordinating their operation as a unified portfolio. Within such systems, dispatch optimization plays a central role because renewable generation, electricity demand, market prices, battery limitations, and grid exchange must be considered simultaneously over time.

This chapter examined the optimization of distributed energy resources and power-flow analysis within a VPP framework. The energy management problem was formulated by considering the electrical power balance, battery SOC dynamics, charging and discharging constraints, grid interaction, electricity prices, and battery degradation costs. Particular attention was given to MILP because of its ability to incorporate both continuous operating variables and discrete operational decisions while considering the intertemporal characteristics of battery storage.

The VPPsim Pro environment was used as a computational case study to demonstrate the proposed approach. The Reference VPP combined 3.6 MW of solar PV generation, 4.2 MW of wind generation, a 2.4 MW/9.6 MWh battery energy storage system, and a 2.2 MW electrical biomass CHP unit. The system was evaluated over a 24-hour horizon together with additional Campus Peak, Wind Firming, and Microgrid configurations. Using the same MILP formulation for all scenarios enabled the influence of resource capacities, demand profiles, renewable generation, storage characteristics, and electricity prices to be examined under a consistent optimization framework.

The simulation results demonstrated substantial differences among the operating characteristics of the four scenarios. Renewable energy utilization ranged from 92.31% to 100%, while battery throughput varied from zero to 12.90 MWh. The Reference VPP achieved 100% renewable utilization but also exhibited the highest grid import and operating cost because of its larger energy demand and volatile price profile. The Microgrid scenario, in contrast, resulted in zero battery throughput. This behavior demonstrated that battery cycling is not necessarily economically advantageous when electricity prices are flat and battery degradation is explicitly included in the optimization objective.

The hourly operation of the Reference VPP further demonstrated the importance of intertemporal optimization. The MILP model charged the battery during relatively low-price periods and discharged stored energy when electricity prices increased, while maintaining the defined SOC and power constraints. These results show that the economic value of battery storage depends not only on installed capacity but also on the temporal relationship among renewable generation, demand, electricity prices, and storage limitations.

The integration of GridLAB-D power-flow analysis provided an additional perspective on network operation. All four evaluated topologies converged successfully, with minimum bus voltages remaining close to 1.0 pu and maximum branch loading remaining below 30% in the implemented models. These results demonstrate the ability of the computational framework to connect VPP configuration and dispatch analysis with network-level calculations. However, the current power-flow implementation represents a simplified snapshot model and should not be interpreted as a validated representation of an actual distribution feeder.

Several limitations also define directions for further development. Renewable generation, demand, and market profiles can be replaced with measured or externally forecast data to improve the realism of the simulations. CHP units, EV charging systems, heat pumps, flexible loads, renewable curtailment, and reactive power can be introduced as independent optimization variables. The power-flow model can also be extended to include explicit generator and inverter injections, user-defined network parameters, and time-series analysis. Integrating these developments with network constraints would enable the transition from sequential dispatch and power-flow calculations toward network-aware VPP optimization.

Overall, the results demonstrate that combining DER aggregation, optimization-based energy management, battery scheduling, and power-flow analysis provides a useful framework for investigating VPP operation. The developed approach offers a reproducible basis for comparing different resource configurations and operating strategies while also highlighting the interactions between economic dispatch and electrical network behavior. Future extensions incorporating measured data, advanced forecasting, flexible demand, and network-

constrained optimization can further improve the applicability of the framework to realistic VPP planning and operation.

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MULTI-BARRIER GEOLOGICAL DISPOSAL DESIGN FOR SPENT NUCLEAR FUEL FROM SMALL MODULAR REACTORS USING DOMESTIC MINERAL RESOURCES

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1. INTRODUCTION

Small Modular Reactors (SMRs) have emerged as an important option in the development of advanced nuclear energy systems because of their modular construction, relatively small unit capacity, and potential for incremental deployment. However, their implementation also introduces specific challenges associated with the back end of the nuclear fuel cycle. Spent-fuel characteristics depend on reactor type, fuel geometry, enrichment, burnup, and irradiation history; therefore, disposal systems developed for conventional reactor fuels cannot necessarily be transferred directly to different SMR concepts without reactor-specific engineering assessment.

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Spent nuclear fuel contains long-lived radionuclides and continues to generate decay heat after removal from the reactor core (Bruno & Ewing, 2006). Deep geological disposal addresses the associated long-term safety requirements by combining engineered and natural barriers to maintain containment and limit radionuclide migration (Birkholzer et al., 2012). One of the most extensively developed approaches is the KBS-3 concept, which combines a corrosion-resistant copper canister, a mechanically resistant cast-iron insert, a compacted bentonite buffer, and the surrounding geological formation (Bennett & Gens, 2008). The effectiveness of such a system depends on the combined thermal, mechanical, hydraulic, chemical, and nuclear-safety performance of its barriers.

The present study considers adaptation of this multi-barrier approach to spent fuel from the VK-300, a boiling water small modular reactor employing hexagonal fuel assemblies. The geometric characteristics of VK-300 fuel differ from the fuel configurations associated with conventional KBS-3 canister arrangements. Consequently, the internal channel configuration, capsule dimensions, structural requirements, decay-heat loading, and criticality control are reconsidered specifically for this fuel geometry.

A further feature of the proposed design is the integration of materials associated with domestic mineral resources in Türkiye. Reşadiye sodium bentonite is considered for the buffer, Gördes clinoptilolite for supplementary radionuclide sorption, Cu-OFP for the corrosion barrier, nodular cast iron for structural resistance, and borated stainless steel incorporating Turkish boron resources for criticality control. In particular, the design introduces a borated stainless-steel layer around the fuel channels and a clinoptilolite-containing bentonite buffer to supplement the conventional barrier functions.

The engineering assessment combines spent-fuel characterization, capsule sizing, thermal analysis, mechanical evaluation, and criticality assessment. OpenMC-based burnup and decay-heat calculations are used to characterize baseline and enriched-fuel scenarios, while analytical and three-dimensional thermal analyses are employed to investigate capsule performance under the repository conditions considered in the study. Mechanical resistance and neutron-absorption capability are subsequently evaluated using screening-level engineering criteria.

The aim of this chapter is to develop and assess a conceptual multi-barrier geological disposal capsule for VK-300 spent fuel by integrating reactor-specific fuel geometry, decay-heat characteristics, engineered barriers, and domestic material resources. The proposed system is intended as an engineering case study rather than a site-specific repository design, providing a framework for examining the adaptation of an established geological disposal concept to BWR-type SMR spent fuel.

2. GEOLOGICAL DISPOSAL OF SPENT NUCLEAR FUEL

2.1. Spent Nuclear Fuel from Small Modular Reactors

The characteristics of spent nuclear fuel are determined by reactor design and operating conditions, including fuel enrichment, discharge burnup, irradiation history, and fuel geometry (DeHart, 1993). Although the chain reaction terminates after removal from the reactor, radioactive decay continues to generate heat, requiring both decay heat and radionuclide inventory to be considered in interim storage and final disposal. These characteristics are particularly relevant to SMRs, which encompass substantially different reactor and fuel configurations

and therefore require reactor-specific assessment of geological disposal systems (Molla, 2025).

In this study, the VK-300 boiling water reactor is selected as the reference SMR. The reactor has a thermal power of 750 MW_{th} and an electrical output of approximately 250 MWe, corresponding to a thermodynamic efficiency of approximately 33%. Its core consists of 313 hexagonal fuel assemblies with an active length of 2.42 m. Each assembly contains 107 fuel rods. The reference design has an average discharge burnup of 41.4 MWd/kgU, a capacity factor of 0.913, and a design lifetime of 60 years (Kuznetsov et al., 2004).

The hexagonal geometry of the VK-300 fuel assembly is particularly important for disposal capsule design. The assembly has a nominal flat-to-flat dimension of approximately 160 mm, while the fuel rods are arranged with a 14 mm lattice pitch. The fuel element outer diameter is approximately 9.12 mm and the pellet diameter is 7.57 mm. These dimensions form the starting point of the dimensional derivation used for the proposed disposal capsule. Instead of adopting the internal geometry of an existing disposal canister directly, the channel dimensions and subsequent capsule dimensions are derived from the actual fuel geometry.

Two fuel conditions are considered in the analysis. The baseline case uses a nominal enrichment of 4.0% and a discharge burnup of 43,500 MWd/tHM, whereas the enriched scenario considers 4.95% enrichment and 55,000 MWd/tHM. The two scenarios allow the influence of higher fuel utilization on the decay-heat characteristics of the spent fuel to be evaluated. The enriched scenario produces the more demanding thermal condition and is therefore used as the governing case for several subsequent design calculations.

2.2. Deep Geological Disposal and the KBS-3 Concept

Deep geological disposal is based on long-term isolation of radioactive waste from the biosphere by placing the waste at sufficient depth within a stable geological formation (Ojovan & Steinmetz, 2022). The safety strategy does not depend on the indefinite performance of a single engineered component. Instead, several independent or complementary barriers are employed so that degradation or reduced performance of one barrier does not immediately result in radionuclide release to the environment (Balčius et al., 2025).

The KBS-3 concept provides the reference architecture for the disposal system investigated in this study. Its fundamental principle is the encapsulation of spent nuclear fuel within a corrosion-resistant metallic canister surrounded by compacted bentonite and emplaced in a deep geological formation. The engineered barrier system and the surrounding host rock collectively provide containment, mechanical protection, groundwater control, and retardation of radionuclide transport.

In the KBS-3 concept, the Cu-OFP outer shell provides corrosion resistance, while the cast-iron insert provides structural resistance against external loads (Raiko et al., 2010). The surrounding compacted bentonite forms a swelling, low-permeability buffer that restricts groundwater transport, retards radionuclide migration, and contributes to mechanical and thermal performance. These engineered barriers operate together with the host rock to provide long-term isolation (Sellin & Leupin, 2013).

Thermal performance is especially important because excessive temperature may adversely affect the long-term properties of the bentonite buffer (Wersin et al., 2007). In the present design, a maximum bentonite temperature of 100 °C is adopted as the thermal design criterion. Consequently, the

permissible heat load of an individual capsule is not determined solely by the quantity of spent fuel that can physically be accommodated. Cooling time, decay heat, buffer properties, repository depth, and the geothermal temperature of the surrounding formation must also be considered.

The reference KBS-3 architecture cannot be transferred to the VK-300 fuel configuration without modification. The proposed capsule accommodates 12 BWR-type fuel assemblies rather than adopting the reference arrangement used for conventional fuel assemblies (Lönnerberg et al., 1983). This geometric difference affects the dimensions of the internal channels, structural insert, copper shell, bentonite annulus, and ultimately the required borehole diameter. The disposal system must therefore be treated as an integrated design problem rather than as a simple replacement of one fuel type with another.

2.3. Adaptation of the KBS-3 Concept to BWR-SMR Fuel

The adaptation of the KBS-3 concept to VK-300 spent fuel requires modification of the internal canister configuration because of the hexagonal geometry and dimensions of the BWR fuel assemblies. Rather than adopting the reference KBS-3 arrangement directly, the proposed design accommodates 12 VK-300 assemblies in a 4×3 configuration. The capsule dimensions are subsequently derived from this arrangement while maintaining the principal functional barriers of the KBS-3 concept.

The proposed architecture consists of individual fuel channels located within a nodular cast-iron structural insert, which is enclosed by a Cu-OFP corrosion barrier and surrounded by a bentonite buffer. Two additional functions are incorporated into the adapted design. First, borated stainless-steel sleeves are introduced around the fuel channels to provide supplementary

criticality control. Second, clinoptilolite is added to the bentonite buffer to enhance the sorption of selected radionuclides, particularly Cs-137 and Sr-90.

This adaptation therefore preserves the multi-barrier philosophy of KBS-3 while modifying the internal configuration and material functions for the VK-300 fuel geometry. The detailed dimensional derivation, material selection, and engineering analyses of the resulting capsule are presented in Section 3.

3. CAPSULE DESIGN AND ANALYSIS METHODOLOGY

3.1. Multi-Barrier Design and Material Selection

The proposed disposal capsule adapts the KBS-3 multi-barrier concept to the geometry of VK-300 spent fuel while considering materials associated with domestic mineral resources in Türkiye. The design accommodates 12 fuel assemblies in a 4×3 configuration. Individual fuel channels are surrounded by borated stainless-steel sleeves and positioned within a nodular cast-iron structural insert. The insert is enclosed by a Cu-OFP shell and surrounded by a bentonite-based buffer containing clinoptilolite.

Each material is assigned a specific engineering function within the barrier system. Reşadiye Na-bentonite provides the principal swelling and low-permeability buffer, while Gördes clinoptilolite is incorporated at 7.5 wt% to provide supplementary sorption of radionuclides such as Cs-137 and Sr-90. Cu-OFP forms the external corrosion-resistant metallic barrier, and EN-GJS-400-15 nodular cast iron provides structural resistance against external pressure. In addition, 316L stainless steel

containing 1.1 wt% boron is used around the fuel channels as an additional neutron-absorbing barrier.

Table 1. Materials and functions of the proposed multi-barrier capsule

Component	Material	Domestic source considered	Primary function
Buffer	Na-bentonite	Reşadiye, Tokat	Hydraulic isolation and swelling
Sorption additive	Clinoptilolite	Gördes, İzmir	Cs-137 and Sr-90 sorption
Outer shell	Cu-OFP	Samsun-Tekkeköy	Corrosion resistance
Structural insert	EN-GJS-400-15 nodular cast iron	Hekimhan-Hasançelebi	Mechanical resistance
Criticality barrier	316L + 1.1 wt% B	Turkish boron resources	Neutron absorption

This configuration distributes the required safety functions among complementary barriers rather than relying on a single material. The domestic-resource framework is therefore integrated into the engineering design according to material function.

3.2. OpenMC Burnup and Decay-Heat Analysis

The spent-fuel characteristics were evaluated using OpenMC v0.13+, an open-source Monte Carlo particle transport code (Romano et al., 2015), with the ENDF/B-VIII.0 nuclear data library. The computational model represented a VK-300 fuel assembly containing 107 fuel rods arranged in a hexagonal lattice with reflective boundary conditions. Depletion calculations employed the 16th-order Chebyshev Rational Approximation Method (CRAM).

Two fuel scenarios were considered. The Baseline case used 4.0% enrichment and a discharge burnup of 43,500 MWd/tHM, whereas the enriched scenario (ENR) used 4.95% enrichment and 55,000 MWd/tHM. The calculated decay heat

was evaluated from the end of irradiation to 40 years of cooling. At 40 years, the heat generation was approximately 52.09 W per assembly for the Baseline case and 67.09 W per assembly for the ENR case. For 12 assemblies, these values correspond to approximately 625 W and 805 W per capsule, respectively. Since the ENR case produces the higher thermal load, it was selected as the governing scenario for subsequent thermal analysis.

A limitation of the calculation is that the depletion analysis employed the chain_endfb71_pwr.xml chain file despite the BWR-type configuration of the VK-300. The use of a PWR-oriented depletion chain for the BWR-type VK-300 configuration introduces additional uncertainty into the calculated actinide inventory. Therefore, the calculated inventory and decay-heat values should be interpreted as engineering estimates, and a BWR-specific depletion chain should be considered in future higher-fidelity analyses.

3.3. Capsule Sizing Methodology

Capsule dimensions were derived progressively from the VK-300 fuel geometry. The fuel assembly has a calculated vertex-to-vertex dimension of approximately 196.3 mm. After incorporating assembly clearance, the fuel-channel inner diameter was selected as 205 mm. A 12 mm borated stainless-steel wall results in an outer channel diameter of 229 mm.

The 12 channels are arranged in a 4×3 configuration with a center-to-center pitch of 239 mm. The resulting array dimensions are 707 mm $\times$ 946 mm. The diagonal dimension governing the required insert diameter is calculated as:

$$d_{array} = \sqrt{(707^2 + 946^2)} = 1181 \text{ mm} \quad (1)$$

After including edge clearance, the structural insert inner diameter was selected as 1,220 mm. A 75 mm insert wall

produces an outer diameter of 1,370 mm. The addition of the 50 mm Cu-OFP shell gives the final capsule diameter:

$$D_{capsule} = 1370 + 2(50) = 1470 \text{ mm} \quad (2)$$

The active channel length is 2,550 mm. Together with the bottom and top closure regions, the total capsule height is 2,700 mm. A 350 mm bentonite annulus surrounding the capsule results in a borehole diameter of 2,170 mm. The final metallic capsule therefore has overall dimensions of 1,470 mm in diameter and 2,700 mm in height.

3.4. Thermal Analysis

Thermal performance was evaluated using both analytical radial heat-transfer calculations and three-dimensional finite element analysis. The analytical model considers steady-state heat conduction through concentric cylindrical layers. The temperature difference across an individual layer is expressed as:

$$\Delta T_{layer} = (Q \ln(r_{outer}/r_{inner})) / (2\pi Lk) \quad (3)$$

where Q is the capsule heat load, L is the active heat-transfer length, k is the thermal conductivity, and r_{outer} and r_{inner} are the outer and inner radii of the corresponding layer.

The governing ENR case uses a 40-year decay-heat load of approximately 805 W and an active length of 2.55 m. Both saturated and dry bentonite conditions were examined. Thermal conductivities of 1.20 W/mK and 0.35 W/mK were used for the saturated and dry conditions, respectively. Under the assumptions of the analytical model, the calculated inner bentonite temperatures were approximately 31.5 °C for the saturated condition and 71.1 °C for the conservative dry condition, both below the adopted 100 °C criterion.

Three-dimensional steady-state thermal analysis was subsequently performed in SimScale using the capsule geometry developed in CATIA V5. Two repository depths were

investigated to evaluate the influence of geothermal conditions: 500 m and 1,000 m. The corresponding external boundary temperatures were 304.7 K (31.55 °C) and 321.1 K (approximately 48.0 °C).

Repository temperature was represented by:

$$T_{depth} = T_0 + Gz \quad (4)$$

where T_0 is the reference surface temperature, G is the geothermal gradient, and z is repository depth. The ENR 40-year condition was applied as the governing heat load. The resulting maximum temperatures were 83.76 °C at 500 m and approximately 100.1 °C at 1,000 m. Thus, the 500 m case remained below the adopted 100 °C criterion, whereas the 1,000 m condition was classified as borderline.

3.5. Mechanical and Criticality Assessment

The mechanical resistance of the structural insert was evaluated using the Lamé thick-wall cylinder formulation. The design pressure was taken as the sum of lithostatic pressure and bentonite swelling pressure:

$$P = P_{lithostatic} + P_{inflation} = 11.92 + 10.00 = 21.92 \text{ MPa} \quad (5)$$

The hoop stress is calculated as:

$$\sigma_{\theta} = P (r_o^2 + r_i^2) / (r_o^2 - r_i^2) \quad (6)$$

For an inner radius of 0.610 m, an outer radius of 0.685 m, and a design pressure of 21.92 MPa, the calculated hoop stress is 189.9 MPa, remaining below the 200 MPa criterion adopted in the study.

Criticality control was assessed through the B-10 areal density of the 12 mm borated stainless-steel sleeve:

$$\rho_{areal} = \rho_{steel} f_B f_{B10} t \quad (7)$$

Using a steel density of 7.85 g/cm³, a boron mass fraction of 0.011, a B-10 isotopic fraction of 0.199, and a thickness of 1.2 cm:

$$\rho_{areal} = 7.85 \times 0.011 \times 0.199 \times 1.2 = 0.02062 \text{ g/cm}^2 \quad (8)$$

The calculated value exceeds the 0.020 g/cm² criterion adopted in the study. Accordingly, the selected insert geometry and borated stainless-steel thickness satisfy the mechanical and criticality screening criteria used for the conceptual capsule design.

4. RESULTS AND DISCUSSION

2.3. Capsule Configuration and Decay-Heat Performance

The proposed configuration accommodates 12 VK-300 spent-fuel assemblies in a 4 × 3 arrangement. The resulting metallic capsule has an outer diameter of 1,470 mm and a total height of 2,700 mm, while the addition of the 350 mm bentonite buffer results in a borehole diameter of 2,170 mm. The total capsule mass, excluding the bentonite buffer, is approximately 30.53 t. The final configuration is shown in Figure 1.

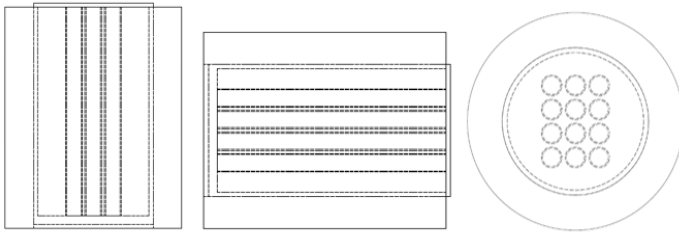


Figure 1. Three-view representation of the proposed multi-barrier disposal capsule.

The decay-heat calculations show a substantial reduction during post-irradiation cooling. The ENR scenario consistently

produces a higher thermal load than the Baseline case and therefore represents the governing condition for thermal assessment.

Table 2. Decay-heat evolution for the Baseline and ENR fuel scenarios

Cooling time	Baseline (W/capsule)	ENR (W/capsule)
End of irradiation	4,979	6,321
1 year	1,953	2,558
3 years	1,135	1,533
5 years	1,060	1,431
10 years	970	1,298
40 years	625	805

At the selected 40-year design point, the capsule heat load decreases to 625 W for the Baseline case and 805 W for the ENR case. The ENR value is approximately 28.8% higher than the Baseline value. At this cooling time, the principal contributors to ENR decay heat are Cs-137, Pu-238, and Am-241, with calculated contributions of 21.18, 17.82, and 13.32 W per assembly, respectively. These results demonstrate that both fuel characteristics and cooling period directly influence the thermal requirements of the disposal system.

4.2. Thermal Performance

The analytical assessment indicates that the 40-year ENR condition satisfies the adopted 100 °C temperature criterion. The calculated inner bentonite temperatures are approximately 31.5 °C under saturated conditions and 71.1 °C under the conservative dry-bentonite assumption. In contrast, at five years of cooling, the ENR heat load of approximately 1,431 W results in a calculated dry-bentonite temperature of approximately 114.4 °C. Thus, the cooling period before emplacement is a significant design parameter.

The three-dimensional analysis shows a maximum temperature of 83.76 °C at 500 m depth, providing a margin of approximately 16.2 K relative to the adopted criterion. At 1,000 m, the maximum temperature increases to approximately 100.1 °C and the condition becomes borderline. The internal temperature differences are nearly identical at the two depths, indicating that the higher maximum temperature at 1,000 m is primarily associated with the increased geothermal boundary temperature.

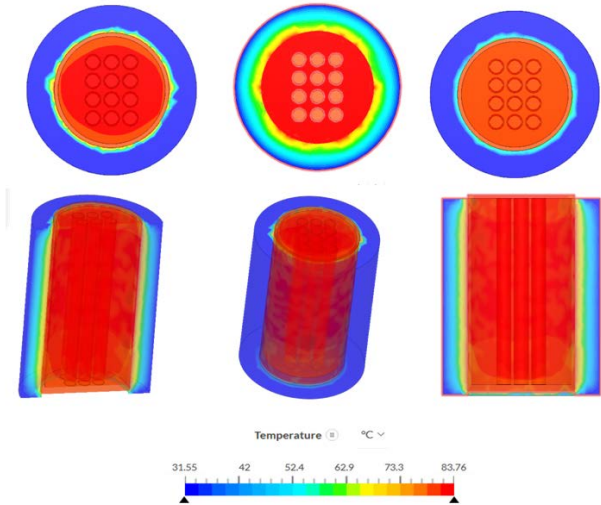


Figure 2. Steady-state temperature distribution of the proposed capsule at 500 m depth for the ENR scenario after 40 years of cooling.

Table 3. Thermal performance at the investigated repository depths

Parameter	500 m	1,000 m
Boundary temperature	31.55 °C	48.0 °C
Maximum temperature	83.76 °C	100.1 °C
Internal temperature difference	52.21 K	52.15 K
100 °C criterion	PASS	BORDERLINE

Under the assumptions of the present analysis, the 500 m condition is therefore thermally more favorable. However, this result should not be interpreted as identifying an optimum repository depth, since actual depth selection requires site-specific geological, hydrogeological, mechanical, and regulatory assessment.

4.3. Mechanical, Criticality, and Sorption Performance

The mechanical analysis indicates that the selected structural insert dimensions satisfy the stress criterion adopted in the design. The calculated hoop stress of the structural insert is 189.9 MPa under the adopted total pressure of 21.92 MPa, remaining below the 200 MPa design criterion. The resulting mechanical margin is approximately 5.1%. For criticality control, the 12 mm borated stainless-steel sleeve provides a calculated B-10 areal density of 0.02062 g/cm², exceeding the adopted minimum value of 0.020 g/cm² by approximately 3.1%.

The clinoptilolite-containing bentonite provides an additional radionuclide-retention function. Based on the material quantities and sorption parameters adopted in the study, the calculated capacities are approximately 1,377.8 mol per capsule for Cs-137 and 688.9 mol per capsule for Sr-90. The combined results therefore indicate that the conceptual design satisfies the mechanical, criticality, thermal, and sorption criteria adopted in this study.

4.4. Engineering Implications and Limitations

Some calculated margins remain limited. In particular, the mechanical margin is approximately 5.1%, the B-10 areal-density margin is approximately 3.1%, and the 1,000 m thermal case is effectively at the adopted temperature limit. The configuration should therefore be considered a conceptual engineering design rather than a repository-ready solution.

Further development would require BWR-specific depletion calculations, detailed three-dimensional criticality and mechanical analyses, experimental characterization of the selected barrier materials, coupled thermo-hydro-mechanical-chemical modeling, and site-specific geological assessment. These analyses would be necessary to verify the long-term performance of the proposed system beyond the screening-level calculations presented in this study.

5. CONCLUSION

This chapter presented a conceptual multi-barrier geological disposal capsule for spent nuclear fuel from the VK-300 boiling water small modular reactor. The design was developed by adapting the fundamental principles of the KBS-3 concept to the geometric and thermal characteristics of VK-300 spent fuel while incorporating materials associated with domestic mineral resources in Türkiye. Rather than directly transferring an existing canister configuration, the capsule dimensions were derived through a continuous engineering chain extending from fuel-assembly geometry to the final borehole dimensions.

The proposed configuration accommodates 12 VK-300 fuel assemblies in a 4×3 arrangement. The final metallic capsule has an outer diameter of 1,470 mm and a total height of 2,700 mm and is surrounded by a 350 mm bentonite buffer. The multi-barrier architecture combines a Cu-OFP outer shell for corrosion resistance, a nodular cast-iron insert for mechanical support, borated stainless-steel sleeves for additional criticality control, and a bentonite-based buffer containing clinoptilolite for hydraulic isolation and supplementary radionuclide sorption.

The decay-heat analysis demonstrated the importance of cooling time in determining the feasibility of geological emplacement. At the selected 40-year design point, the calculated

capsule heat loads were approximately 625 W for the Baseline fuel scenario and 805 W for the higher-enrichment ENR scenario. The ENR condition was therefore used as the governing case for the thermal assessment. Analytical calculations showed that the 40-year cooling condition satisfied the adopted 100 °C bentonite temperature criterion under both saturated and conservative dry-buffer assumptions, whereas the five-year ENR condition exceeded this limit under the dry-buffer assumption.

The three-dimensional thermal analysis further demonstrated the importance of repository depth and geothermal boundary conditions. At 500 m depth, the maximum calculated temperature was 83.76 °C, providing a margin of approximately 16.2 K relative to the adopted 100 °C criterion. At 1,000 m depth, the maximum temperature increased to approximately 100.1 °C and was therefore classified as a borderline condition. The nearly identical internal temperature differences obtained for the two depth scenarios indicate that this increase was primarily caused by the higher geothermal boundary temperature at greater depth.

The mechanical and criticality assessments also supported the feasibility of the conceptual configuration within the assumptions of the study. The calculated hoop stress of the structural insert was 189.9 MPa, remaining below the adopted 200 MPa criterion. The B-10 areal density of the 12 mm borated stainless-steel layer was calculated as 0.02062 g/cm², exceeding the specified minimum value of 0.020 g/cm². The incorporation of Gördes clinoptilolite into the bentonite buffer additionally provided a supplementary sorption function for Cs-137 and Sr-90.

The results collectively demonstrate that adaptation of a geological disposal concept to SMR spent fuel requires consideration of fuel geometry, isotopic inventory, decay heat, material properties, mechanical loading, criticality control, and

repository conditions as an integrated engineering problem. They also indicate that domestic mineral resources can be considered according to specific functional requirements within a multi-barrier disposal architecture rather than solely from the perspective of material availability.

The proposed capsule should, however, be regarded as a conceptual engineering design rather than a repository-ready or licensing-level solution. Further development would require BWR-specific depletion calculations, detailed three-dimensional criticality analysis, experimental characterization of the selected materials, coupled thermo-hydro-mechanical-chemical modeling, long-term corrosion and mechanical assessments, and site-specific geological and hydrogeological investigations. Within these limitations, the study provides a systematic framework for investigating the adaptation of multi-barrier geological disposal systems to SMR spent fuel and for evaluating the potential integration of domestic mineral resources into future nuclear waste management technologies.

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EQUIPMENT SELECTION, SIZING, AND SYSTEM INTEGRATION IN BIOGAS PLANTS

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1. INTRODUCTION

Among renewable energy sources, biogas represents one of the few systems that can simultaneously address organic waste management and energy production. Anaerobic digestion (AD) technology is based on the decomposition of organic matter by microorganisms under oxygen-free conditions. Therefore, environmental and operational parameters such as temperature, condensation, and gas-flow control play a decisive role in process performance (Abbasi et al., 2012). The economic and technical success of a biogas plant depends not only on understanding the biological processes involved, but also on the careful design of the engineering infrastructure required to support them.

The selection and sizing of plant equipment directly affect operating costs, environmental compliance, and system reliability

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throughout the facility's lifetime. An improperly sized reactor may disturb the stability of the biological process, while an inadequate mixing system can lead to stratification and the formation of dead zones, resulting in a substantial reduction in gas production (Ward et al., 2008). Conversely, oversized systems may create unnecessary capital costs and can adversely affect process stability when operated under low organic loading conditions.

This chapter addresses the main engineering challenges encountered in biogas plant design and presents solution-oriented approaches to these issues. Reactor selection criteria, sizing calculations, mixing systems, substrate feeding technologies, gas storage equipment, and plant installation procedures are examined systematically with reference to current literature. The aim of the chapter is to provide a comprehensive technical reference for both design engineers and plant operators.

2. REACTOR DESIGN AND SIZING

The reactor is the core component of an anaerobic digestion plant. The choice of reactor type should be based on an integrated assessment of several factors, including substrate characteristics, plant capacity, energy requirements, and local climatic conditions. Available reactor technologies range from simple open lagoons to enclosed two-stage systems.

Substrate characterization is the primary factor in reactor selection. Plug-flow reactors or two-stage systems are generally preferred for substrates with a high total solids (TS) content, whereas low-viscosity liquid substrates are more suitable for continuously stirred tank reactors (CSTRs) (Angelidaki et al., 2011). To maintain stable operation, key substrate properties such as biological oxygen demand (BOD), chemical oxygen demand

(COD), and the volatile fatty acid (VFA) profile should also be determined.

Plant scale is another important consideration. In small-scale farm applications, simple CSTRs or dome-type digesters are often favored because of their cost-effectiveness. In contrast, municipal waste treatment facilities can benefit from upflow anaerobic sludge blanket (UASB) or granular sludge reactors, particularly where high organic loading rates are required, and energy efficiency is a major concern (Lettinga, 1995). A third parameter influencing reactor selection is the need to achieve an appropriate balance between capital and operating costs. The main characteristics, operating ranges, advantages, and limitations of the most used biogas reactor types are summarized in Table 1. Hydraulic retention time (HRT) is the average period during which the substrate remains in the reactor and is a key parameter governing the efficiency of anaerobic digestion. It is determined by the relationship between the effective reactor volume and the daily substrate flow rate. In general, a larger reactor volume or a lower feed rate results in a longer retention time, whereas increasing the feed rate shortens the time available for biological degradation. Typical HRT values for animal manure range from 15 to 30 days, while shorter retention periods of approximately 8–20 days may be suitable for industrial organic wastes (Weiland, 2010).

The organic loading rate (OLR) describes the amount of volatile solids (VS) introduced into the reactor per unit volume each day and is commonly expressed as kg VS/m³/day. Increasing the OLR can increase gas production up to the system's loading capacity. However, excessive loading may result in volatile fatty acid (VFA) accumulation, pH imbalance, and eventually process instability or failure. Optimum OLR ranges of 2–4 kg VS/m³/day for mesophilic systems and 4–7 kg VS/m³/day for thermophilic

systems have been reported in the literature (Schnürer and Jarvis, 2010).

Anaerobic digestion processes are generally operated within two main temperature ranges according to microbial activity: mesophilic conditions at approximately 35–40 °C and thermophilic conditions at approximately 50–55 °C. The design of the heating system should consider reactor volume, surface area, inlet substrate temperature, local climatic conditions, and the relevant heat-loss coefficients.

The thermal balance of the reactor includes the energy required to heat the incoming substrate, heat losses through the reactor walls by conduction and convection, and conductive losses to the ground. Waste heat recovered from the cogeneration unit should be used as the primary source for meeting the heating demand. When this source is insufficient, auxiliary heating systems may be required. Insulating the reactor surface with materials such as polyurethane or glass wool can reduce heat losses by approximately 40–60% (Sinha and Pandey, 2011).

Table 1. Comparison of Biogas Reactor Types

Reactor Type	Operating Principle	HRT (days)	OLR (kg VS/m ³ /day)	TS Tolerance (%)	Advantages	Disadvantages
CSTR (Continuously Stirred Tank Reactor)	Continuous feeding with mechanical mixing	15–30	1.5–4.5	5–15	Simple design; widely used	Requires a relatively large reactor volume
UASB (Upflow Anaerobic Sludge Blanket)	Granular sludge with upward-flow hydrodynamics	1–5	5–20	1–3	Low energy demand; high OLR capacity	Limited to substrates with low TS content
PFR (Plug-Flow Reactor)	Horizontal flow with limited mixing	20–40	2–5	10–20	Suitable for high-TS substrates; limited back-mixing	High risk of clogging
AF (Anaerobic Filter)	Biofilm attached to fixed packing media	1–3	5–15	1–5	Long SRT; low biomass washout	Clogging and more complex maintenance
Two-Phase System	Separate reactors for acidogenic and methanogenic stages	10–20	3–8	5–20	Improved pH control; stable operation	High capital cost

3. MIXING AND HOMOGENEOUS DISTRIBUTION

The mixing system promotes a uniform distribution of the substrate within the reactor, thereby improving contact between the substrate and microorganisms, reducing temperature gradients, and preventing gas bubbles from becoming trapped in the slurry. Inadequate mixing can lead to the accumulation of coarse floating solids at the surface, the formation of bottom sediments, and a reduction in the effective reactor volume.

Mixing intensity is commonly expressed as the power input per unit reactor volume (W/m^3). Insufficient mixing may create dead zones and reduce substrate homogeneity, whereas excessive mixing can disrupt granular sludge structures and impair biological process performance (Kaparaju et al., 2008). For CSTR systems, a mixing intensity of approximately $5\text{--}10 \text{ W}/\text{m}^3$ is generally considered adequate. For multiphase substrates and highly viscous mixtures, this value may increase to around $15 \text{ W}/\text{m}^3$.

The choice between continuous and intermittent mixing is another factor that can influence process efficiency. Intermittent mixing, for example for 3–4 hours per day, may provide biogas production comparable to that achieved with continuous mixing while reducing energy consumption by approximately 30–40% (Stroot et al., 2001). This represents an important opportunity to improve the plant's overall energy efficiency.

Mechanical mixing can be achieved using vertical-shaft mixers, horizontal-shaft mixers, or submersible mixing devices. One of the main advantages of these systems is that the mixing intensity can be precisely adjusted via speed control. Their main limitations are the higher energy demand associated with viscous substrates and the increased risk of mechanical failure.

Pneumatic mixing involves recirculating the biogas produced in the reactor and reinjecting it under pressure near the bottom of the vessel using a compressor. The external energy requirement of this method is relatively low; however, care must be taken to prevent air ingress, as this may adversely affect gas quality and process safety.

Hydraulic mixing relies on pumping and recirculating the substrate through different points of the reactor. Owing to its relatively simple configuration and lower equipment requirements, it can offer an economical alternative, particularly for small-scale biogas plants. The main technical characteristics, operating requirements, and practical limitations of mechanical, pneumatic, and hydraulic mixing systems are compared in Table 2. Optimizing mixing energy is a critical design consideration because it directly affects the plant's overall energy balance. Such optimization generally accounts for substrate rheology, reactor geometry, and flow behavior, as assessed through computational fluid dynamics (CFD). CFD analysis is increasingly used to predict mixing performance prior to plant construction and to identify operating conditions that minimize dead-zone formation in the reactor (Wu, 2010).

Energy-recovery strategies can further improve overall efficiency. Waste heat generated by mixing motors may be recovered and used to support reactor heating, while variable-frequency drives (VFDs) can automatically adjust mixing speed according to changes in substrate loading. Together, these approaches can reduce unnecessary energy consumption and improve the digestive system's energy performance.

Table 2. Technical Comparison of Mixing Systems

Parameter	Mechanical Mixing	Pneumatic Mixing	Hydraulic Mixing
Energy Consumption	2–5 W/m ³	0.5–2 W/m ³ (using biogas)	1–3 W/m ³
TS Compatibility	Wide range (3–15%)	Low TS (<5%)	Moderate TS (3–10%)
Maintenance Requirement	Moderate to high (moving parts)	Low (mainly compressor maintenance)	Low
Foam Control	Good (surface-driven mixing)	Limited (gas-bubble mixing)	Moderate
Capital Cost	High	Moderate	Low to moderate
Typical Application Scale	Suitable for all scales	Generally preferred for large-scale plants	Small- to medium-scale plants
Scaling/Fouling Risk	Low	Moderate	Moderate

4. SUBSTRATE FEEDING AND LOADING SYSTEMS

The substrate feeding system controls the introduction of organic material into the anaerobic reactor and therefore directly influences process stability. Feeding frequency, feed volume, and substrate pretreatment conditions are all important in maintaining a stable microbial community and consistent gas production.

Liquid substrates, including animal manure, liquid fractions of food waste, and industrial wastewater, are generally transferred to the reactor by gravity or pumping systems. Submersible, centrifugal, and screw pumps are among the most used equipment for this purpose. Pump selection should reflect the viscosity and solids content of the substrate. Positive-displacement pumps are generally more suitable for liquids with a high solids content.

To reduce the effect of sudden changes in substrate loading on the microbial population, feeding is preferably carried out automatically at short intervals, for example, hourly or every few hours. Sudden loading shocks may disturb the pH balance,

promote volatile fatty acid (VFA) accumulation, and eventually lead to process inhibition (Mata-Alvarez et al., 2000).

Solid substrates such as maize silage, wheat straw, and the organic fraction of municipal solid waste require dedicated loading equipment. Belt conveyors, screw conveyors, and piston-type feeders are commonly used for this purpose. In many plants, batch feeding is more practical than continuous feeding for solid materials, although it may also increase the likelihood of short-term loading shocks within the reactor.

One of the main concerns in solid-substrate feeding systems is preventing contact between the reactor gas space and ambient air. Airlock arrangements, double-door feeding chambers, or specially designed sealing mechanisms can be used to limit air ingress and gas leakage. These measures are important both for explosion safety and for reducing methane losses.

Co-digestion involves the simultaneous digestion of two or more substrates and is commonly used to improve the carbon-to-nitrogen ratio and obtain beneficial interactions between feedstocks. For example, combining animal manure with relatively low-C/N plant residues can reduce ammonia inhibition and increase gas yield by approximately 20–80% (Mata-Alvarez et al., 2014).

Substrate pretreatment may include mechanical size reduction, thermal hydrolysis, ultrasonic treatment, and alkaline pretreatment. Thermal hydrolysis, typically carried out at approximately 150–170 °C for 30–60 minutes, is particularly effective for waste-activated sludge because it disrupts cellular structures and improves biodegradability (Bougrier et al., 2008). From an economic perspective, the additional cost of substrate preparation should be weighed against the increase in biogas production and the associated revenue.

5. GAS STORAGE AND SAFETY EQUIPMENT

Biogas production may vary on both daily and seasonal timescales depending on feeding patterns and biological activity. Gas storage systems are therefore used to balance differences between production and consumption, improve plant safety, and support the continuous operation of energy-conversion units.

Common storage solutions include flexible single- or double-membrane gas holders installed above the reactor, fixed above-ground steel tanks, and inflatable roof systems integrated into the reactor structure. Membrane gas holders are widely used because they can provide relatively large storage volumes at low operating pressures, typically 5–30 mbar, while offering structural flexibility and comparatively favorable installation costs.

Required storage capacity is generally determined from the average biogas production rate and the desired buffer period. For small plants, a storage volume corresponding to approximately 4–8 hours of normal gas production is often sufficient. Larger facilities may require a buffer capacity equivalent to 8–24 hours of production. In practical terms, the required storage volume is obtained by multiplying the average hourly biogas production rate by the desired storage duration.

Safety systems are essential not only for regulatory compliance but also for maintaining continuous and reliable plant operation. Safety valves, pressure-relief valves, and vacuum breakers should be installed at appropriate locations along gas storage and distribution lines. In the event of excessive pressure, automatic flare systems can be activated to combust surplus biogas, thereby limiting the direct release of methane into the atmosphere.

Flame arresters are used to prevent flame propagation back through the gas line in the event of ignition or flashback and

should be installed at critical connection points. Equipment used in potentially explosive atmospheres should comply with the relevant ATEX requirements and applicable national standards, including TS EN 13463 where appropriate, to provide adequate protection against ignition hazards.

Gas monitoring systems measure both the quantity of biogas produced and its composition, either continuously or at defined intervals. Flow meters are used to monitor gas production rates, while gas analyzers based on electrochemical or infrared measurement principles can determine the concentrations of methane (CH₄), carbon dioxide (CO₂), hydrogen sulfide (H₂S), and oxygen (O₂) in real time.

Hydrogen sulfide is commonly present in biogas at concentrations ranging from approximately 100 to 10,000 ppm. It can cause severe corrosion in process equipment and represents a significant health hazard. For this reason, biogas should be treated to remove H₂S before being supplied to energy-conversion units. Common treatment methods include biological desulfurization, activated-carbon filtration, and the addition of iron chloride (Ryckebosch et al., 2011).

6. PLANT INSTALLATION AND COMMISSIONING PROCESS

Plant installation is the stage at which the technical specifications defined during design are implemented on site. Coordination of construction and installation activities, execution of commissioning procedures, and final performance testing are the main steps that determine whether the completed facility meets its design requirements.

Construction of a biogas plant generally includes site preparation and foundation excavation; construction of the

reactor in concrete or steel; installation of piping and cable infrastructure; electrical and automation systems; insulation and external cladding; and installation of gas lines and safety equipment.

During reactor construction, concrete quality control and gas-tightness testing are particularly important. A minimum concrete grade of C25/30 should be used where reinforced concrete is employed. Concrete surfaces exposed to potentially aggressive process conditions should also be protected with suitable coatings or membrane systems to reduce the risk of long-term deterioration and leakage. Equipment installation should follow the manufacturer's specifications, including the recommended tightening torques, vibration-isolation requirements, and provisions for thermal expansion.

Commissioning begins after completion of the mechanical installation and involves a systematic sequence of testing and verification. Pipework is first subjected to hydrostatic pressure testing, followed by leak testing of gas lines using nitrogen or another suitable inert gas. Before pumps, mixers, and other rotating equipment are placed into service, lubrication, alignment, and no-load operating checks should be completed.

A biological start-up requires the reactor to be seeded with an appropriate inoculum. Active sludge from a comparable anaerobic digestion plant or sludge from a wastewater treatment facility may be used for this purpose. During the initial start-up period, typically lasting around 4–8 weeks, the organic loading rate is kept relatively low and increased gradually to allow the microbial community to adapt to the substrate. Daily monitoring of pH, the relationship between volatile fatty acids and alkalinity, and biogas composition provides important information on the stability and development of the process.

Performance testing is normally carried out by operating the plant at or near its design capacity for a defined period, typically 30 to 90 days, and verifying the agreed-upon performance indicators. Typical acceptance criteria include specific methane yield expressed as $\text{L CH}_4/\text{kg VS}$, volumetric methane production expressed as $\text{m}^3 \text{CH}_4/\text{m}^3 \text{ reactor/day}$, volatile solids removal efficiency, and methane concentration in the produced biogas, with minimum values commonly specified in the range of 52–55% CH_4 .

During acceptance testing, calibration records for all measurement instruments should be current, operating data should be recorded continuously, and key measurements should be checked against appropriate reference methods. Once the required performance values and contractual guarantees have been demonstrated, the plant can be formally accepted and transferred to the operator.

7. CONCLUSION

The selection, sizing, and integration of equipment in a biogas plant are fundamental engineering considerations for the successful implementation of anaerobic digestion at an industrial scale. The discussion presented in this chapter shows that reactor selection should be guided primarily by substrate characteristics and that operating parameters such as hydraulic retention time (HRT) and organic loading rate (OLR) require careful optimization to maintain stable and efficient operation.

About mixing, intermittent operation can offer considerable energy-saving potential compared with continuous mixing, provided that adequate substrate homogeneity is maintained. Substrate feeding systems should likewise be designed with close attention to process stability and plant safety,

while opportunities for co-digestion should be evaluated according to feedstock availability and compatibility.

The appropriate selection and installation of gas storage and safety equipment in accordance with relevant international standards are essential for both regulatory compliance and safe plant operation. Commissioning and performance testing are equally important, as they provide objective evidence that the completed facility meets its intended design and operating targets.

Future developments are expected to place greater emphasis on intelligent control systems that use real-time sensor data, digital-twin approaches for reactor monitoring and optimization, and in situ biomethanation technologies to convert carbon dioxide into additional methane. These developments may contribute to more efficient, flexible, and better integrated biogas plants while improving the overall utilization of the energy contained in organic waste streams.

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