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Flexibility Deployment in the 2050 Dutch Power System: A Seasonal Operational Assessment

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Abstract—As the Netherlands moves toward climate neutrality by 2050, the national power system will rely heavily on variable renewable energy sources (VRES) such as offshore wind and solar photovoltaics. While previous studies have examined steady-state implications of overplanting and grid reinforcement, less attention has been given to assessing the effectiveness of flexibility resources during longer time periods. This paper presents an operational assessment of the 2050 Dutch transmission system using full-day optimal power flow simulations for typical summer and winter conditions.

The synthetic model of the transmission system is developed in DIgSILENT PowerFactory and includes distributed and centralized supply, batteries, electrolyzers, and demand response mechanisms. Using the Mean-Variance Mapping Optimization (MVMO) algorithm with 15-minute resolution, system operation is optimized to minimize active power losses while respecting voltage and thermal limits. The results show that flexibility resources are essential to ensure demand coverage and reduce transmission congestion, especially during periods of high VRES generation. In winter, the centralized nature of offshore wind leads to regional overloads and higher losses, while summer benefits from decentralized PV generation and more balanced load matching. Batteries and hydrogen units show distinct operational patterns, emphasizing the importance of their strategic placement. These findings support the design of control strategies and infrastructure planning for high-VRES transmission systems.

Index Terms—Dutch power system, synthetic grid modeling, power system planning, voltage regulation, active power losses, PowerFactory, renewable integration, operational scenarios.

I. INTRODUCTION

The European Union and the Dutch government are accelerating the energy transition to reach climate neutrality by 2050 [1], [2]. This transition involves high penetration of variable renewable energy sources (VRES), such as wind and solar, posing technical challenges related to intermittency, grid stability, and operational reliability, along with uncertainty around infrastructure adequacy and flexibility needs.

A key goal for the Netherlands is to achieve a fully circular economy by 2050 [3]. A significant share of offshore wind

power is expected to be used for hydrogen production, supporting the country's ambition to become a European hydrogen hub [4].

Several studies have examined long-term energy planning and scenario development for the Dutch power system. They include Netbeheer Nederland's roadmap outlining four governance-driven pathways [5]; CE Delft's analysis of future-proof grid development [6]; Berenschot's four climate-neutral 2050 scenarios [7]; and TenneT and Gasunie's Infrastructure Outlook 2050 plus its Phase II follow-up quantifying cross-carrier infrastructure consistent with $\approx 95\%$ CO₂ reduction [1], [2]. Studies on PV overplanting document trade-offs between renewable capture and grid reinforcements [8], but these works generally use simplified operating conditions and overlook dispatch constraints of flexibility resources over representative daily cycles.

This research assesses system behavior based on technical performance metrics such as losses, voltage drop, grid congestion, and flexibility usage over a typical operational day. We focus on the time-resolved steady-state operation of the 2050 Dutch power system. Synthetic Dutch transmission system models developed in [8], [9] are used as starting points, with the subsequent incorporation of centralized and decentralized generation, hydrogen-based power plants, batteries, and demand response resources. Two representative days are selected, one in summer and one in winter, to capture the seasonal variability in renewable generation and demand. A sequence of steady-state optimal power flow calculations is performed every 15 minutes using the Mean-Variance Mapping Optimization (MVMO) algorithm to determine the optimal dispatch of flexible resources while minimizing active power losses and ensuring secure operation.

The remainder of this paper is organized as follows: Section II describes the synthetic power system model and the scenario preparation process. Section III outlines the simulation methodology. Section IV presents and compares the

operational outcomes for summer and winter days. Section V discusses the implications of the findings in terms of flexibility deployment, grid stress, and planning considerations. Finally, Section VI concludes with key insights and recommendations for the design and control of high-VRES power systems.

II. 2050 DUTCH GRID MODEL AND SCENARIO DEFINITION

A. Synthetic Grid Model Structure

The synthetic grid model represents the Dutch transmission network and was built in DIGSILENT PowerFactory. The model was initially based on a 2030 model, developed in [9], [10]. It was expanded and spatially aggregated using diagrams from [11] and ongoing or planned projects listed in [12]. Additional network expansions were added in [8]. The network is divided into regional zones, as shown in Fig. 1, and each zone includes generation, demand, and flexibility resources distributed proportionally according to municipal-level projections from [13].

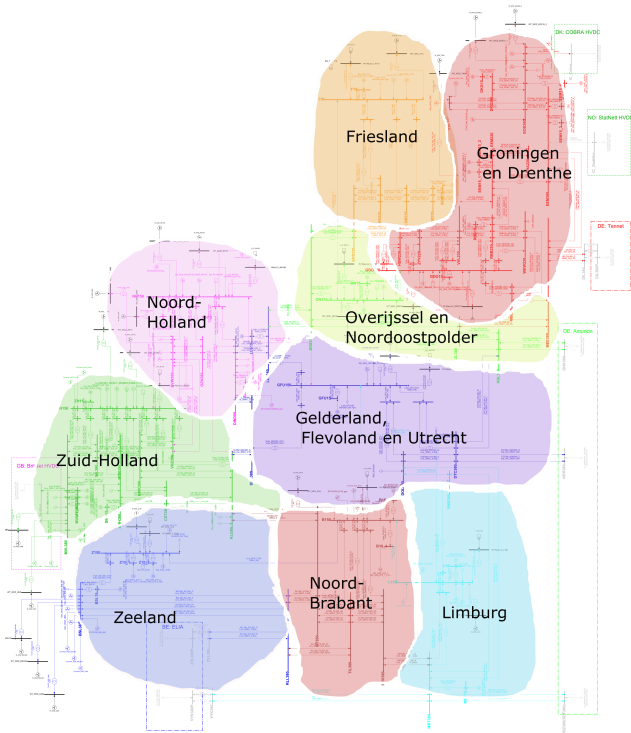


Fig. 1: Dutch power system division into zones

The baseline synthetic model comprises busbars (110/150/220/380 kV), transmission lines, synchronous machines, static generators (representing VRES such as wind and PV), generalized loads for residential and industrial demand, and interconnections to neighboring systems and the underlying distribution networks (modeled as general loads with power equal to the corresponding power flows). This setup enables system-wide, time-resolved assessment of congestion patterns, flexibility utilization, and operational stress under diverse seasonal and daily conditions.

B. Supply, demand, and flexibility capacities

Assumptions were drawn from the National 2050 scenario for the Netherlands [5]. This scenario emphasizes centralized planning, large-scale offshore wind deployment, and a high degree of electrification across all sectors. It also incorporates the use of nuclear energy, demand-side response, battery storage, and hydrogen-based flexibility options.

We then updated this scenario using recent government and industry reports [1]–[4] to reflect the expected 2050 scale. Table I summarizes the installed capacities for generation, demand, and flexibility technologies.

TABLE I: Supply, Demand, and Flexibility Mix in the 2050 National Scenario [8]

Supply Technology	Capacity [GW]
Solar PV (onshore + offshore)	106.5
Onshore (roofs + fields)	96.5
Offshore	10.0
Wind Power (onshore + offshore)	71.5
Onshore	20.0
Offshore	51.5
Hydrogen Power Plants	31.5
Large Unit	19.0
Small Unit	12.5
Nuclear Power	3.0
Total Supply	212.5
Peak Demand Category	Peak [GW]
Households	7.0
Services	7.0
Industry	18.0
Transport	5.0
Agriculture	4.0
Other	1.0
Total Electricity Demand	40.0
Flexibility Option	Capacity [GW]
Electrolyzers	50.6
Battery Storage (Centralized + Decentralized)	53.4
Centralized	26.7
Decentralized	26.7
Demand Response (Industrial + Thermal)	16.2
Industrial Demand Side	5.2
Smart Heat Pumps for Buildings	7.0
Electric Boilers for Industry	4.0
Total Flexibility	120.2

Additional adjustments were implemented, as detailed in [8]: 10 GW of PV placed offshore, floating in between wind turbines [14]; 3 GW reallocated from large gas to nuclear at Borssele [15]; and demand response potentials (adjustment of electricity consumption according to price signals and grid necessity) of 5.2 GW for industry [16], 7 GW for smart heat pumps [17], and 4 GW for industrial electric boilers [17].

A PV overplanting ratio of 60% is assumed throughout this study, meaning that the grid connection capacity for solar power is limited to 60% of the installed panel capacity. This value reflects the optimal trade-off between network investment and performance, as identified in previous work [8].

III. OPERATIONAL SIMULATION FRAMEWORK

A. Problem Formulation

The full-day simulations are formulated as a sequence of optimal power flow (OPF) problems, focused on economically dispatching generation and flexibility resources while satisfying network constraints. The objective is to minimize system losses and voltage deviations while respecting the operational limits of generation units, storage systems, and transmission assets.

MVMO was selected to solve the OPF problem at each time step. MVMO is a population-based stochastic optimization technique that shares characteristics with other heuristic methods but introduces a unique mapping function for generating new candidate solutions. This function uses the mean and variance of the best-performing individuals in the population to guide the mutation process, ensuring all new solutions remain within predefined variable bounds.

As the search progresses, the shape and position of the mapping curve adapt, allowing MVMO to balance global exploration and local refinement. By updating candidate solutions around the current best solution in each iteration, MVMO effectively avoids premature convergence and reaches near-optimal solutions with high computational efficiency [18].

B. Selection of Representative Days

Two representative days were selected to capture the seasonal variation in generation and demand patterns. Weather data from January 5th, 2022, and July 17th, 2022, were used to define the winter and summer days, respectively. These dates were chosen randomly and scaled to represent projected system conditions in 2050.

- **Summer Day:** Characterized by high solar generation, moderate wind, and relatively low space heating demand.
- **Winter Day:** Dominated by high offshore wind generation, minimal solar output, and elevated electricity demand from heating and industrial processes.

The system demand curve results from combining residential, commercial, and industrial load profiles, adapted from [19]–[21]. These are scaled to match the estimated daily demand levels for 2050. Notably, residential demand shows a higher peak on winter days due to heating loads.

C. Time-Series Optimization with MVMO

The optimization process is repeated every 15 minutes, enabling time-resolved simulation of system behavior across an entire day. At each 15-minute timestep, the objective is to minimize:

- Operating costs.
- Total active power losses in transmission lines and transformers.
- Voltage magnitude deviations from nominal values.
- Use of flexibility resources, subject to operational limits.

The optimization is constrained by:

- Active and reactive power balance at each bus.
- Operating limits of generators and flexibility resources.

- Thermal limits on lines and transformers.
- Voltage magnitude thresholds ($\pm 5\%$ of nominal).
- Ramp rates and energy capacity limits of batteries and electrolyzers (including storage units).
- Demand satisfaction for each region at each timestep.

All generation technologies, including PV, wind, hydrogen-fueled thermal units, and batteries, are considered dispatchable within predefined availability profiles and capacity limits. The only exception is the nuclear power plant, modeled as non-dispatchable baseload due to its limited short-term flexibility. It operates close to nominal output throughout the day.

Other thermal units are assumed to run on hydrogen. By 2050, hydrogen infrastructure is expected to be well established, potentially repurposing existing high-pressure gas pipelines (67 and 80 bar). These hydrogen-fueled units can inject or absorb reactive power when online [4].

PV systems are equipped with inverter-based voltage regulation and operate as static synchronous compensators (STATCOMs) when active power output remains below 95% of their rated capacity. Their reactive support capability is therefore reduced during periods of high solar production [10].

Demand response is modeled as a partially controllable load block, with predefined sector-specific activation limits. However, demand response is left as the last option for flexibility on both representative days.

D. Simulation Flow and Post-Processing

For each day, the simulation follows the sequence:

- 1) Load and generation profiles are assigned to each region and busbar.
- 2) MVMO is applied at each timestep to determine feasible and optimal dispatch settings.
- 3) Power flow calculations validate the feasibility and record system states (e.g., losses, voltages, loading).
- 4) Flexibility usage, congestion levels, and performance metrics are logged over the 96 intervals of the day.

Post-processing is performed to extract:

- Time series of dispatched power from each resource type.
- Active power loss curves.
- Line loading and transformer utilization levels.
- Frequency and duration of constraint violations (if any).
- Distribution of reactive power support across the network.

The output data is then analyzed to compare system performance between the two seasonal conditions and to understand the operational role and value of different flexibility options.

IV. SIMULATION RESULTS

A. Operating Costs for Winter and Summer Days

Table II displays the accumulated costs of each technology for both days.

B. Winter Day Operation

The winter day features high wind infeed, minimal solar generation, and demand driven by heating and industry, as shown in Fig. 2a.

TABLE II: Daily Operating Costs

	Winter Day [k€]	Summer Day [k€]
Power Supply		
Offshore Wind Power	23 248.8	4969.9
Onshore Wind Power	2428.6	631.6
Offshore Solar Power	239.6	2168.1
Onshore Solar Power	1369.8	14 526.5
Hydrogen Power Plant	6695.3	1610.8
Nuclear Power Plant	31 104.0	31 104.0
Flexibility		
Electrolyzer	5217.8	5216.4
Centralized Battery	3670.7	7101.1
Decentralized Battery	1317.4	12 796.7
Penalty Cost		
Active Power Losses	44 958.7	26 795.7
Total (incl. penalty cost)	120250.6	106920.7

Fig. 3a shows the dispatch of flexibility resources, which is characterized by:

- **Batteries:** Due to the centralized nature of wind generation, mostly batteries near offshore wind connections were charged and provided supply support at night. Decentralized units are underutilized due to congestion.
- **Electrolyzers:** Activated overnight and midday in areas with offshore wind surpluses. Dispatch is curtailed in certain regions due to limited transmission capacity.
- **Demand Response:** Significant activation, particularly in early morning and evening hours.

Congestion emerges as a key issue in regions heavily reliant on offshore wind, as revealed through the steady-state power flows computed for each 15-minute interval. Some transmission lines operate near or at thermal limits, particularly those linking coastal zones to the center and south of the country.

Active power losses rise to approximately 5.8%.

C. Summer Day Operation

In contrast, during the summer day, solar power dominates generation in most regions, with limited wind supply, as shown in Fig. 2b.

Fig. 3b shows the dispatch profiles for key generation and flexibility sources, which are characterized by:

- **Batteries:** Discharged during evening demand peaks and recharged during mid-day solar surplus. Decentralized batteries, located close to demand, reduce the need for long-distance transmission.
- **Electrolyzers:** Activated during mid-day solar peaks. Their dispatch is regionally skewed toward areas with lower local demand, helping absorb excess power.
- **Demand Response:** Minor activation due to relatively low system stress. Mainly observed in early evening hours.

The system operates mostly within thermal limits throughout the day. Peak line loading occurs during the afternoon export of solar power from high-PV regions, but does not result in overloads.

Total active power losses remain below 4% of supplied energy. Voltage deviations are minimal, aided by distributed

generation and the STATCOM-like operation of PV inverters. Only two busbars briefly required reactive compensation support due to local mismatches between supply and demand.

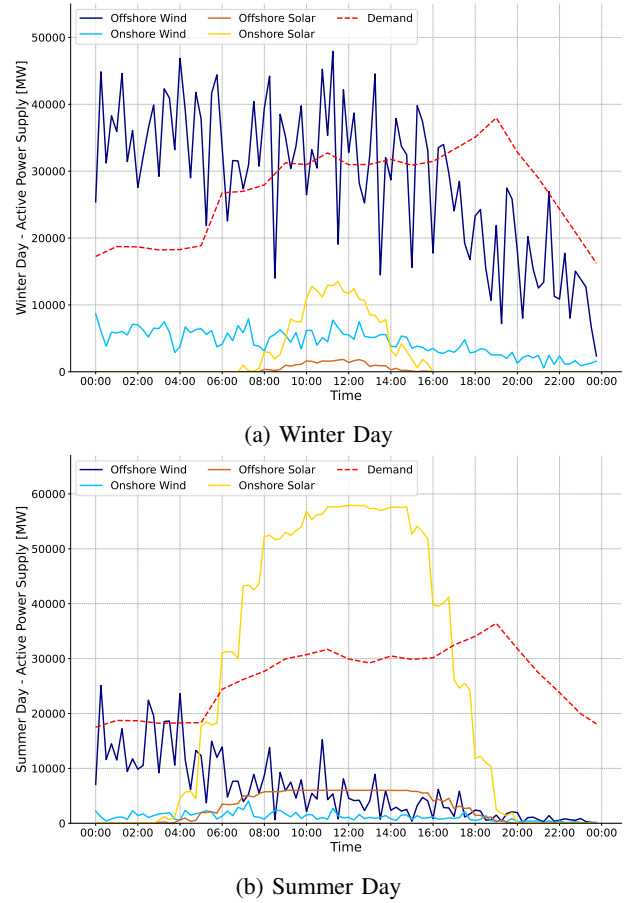
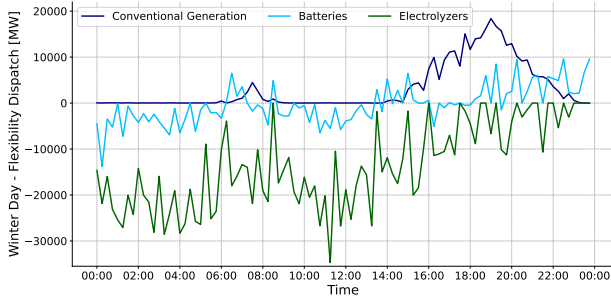


Fig. 2: Time-series of VRES generation and demand for typical winter and summer days.

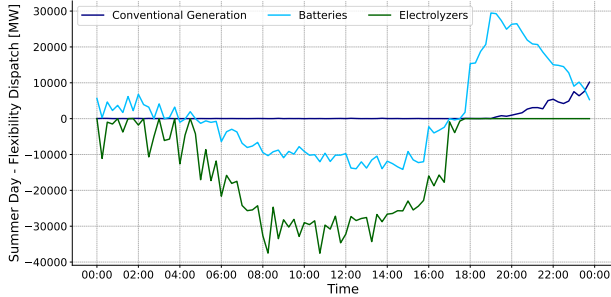
D. Grid Stability

Looking at Fig. 4, active power losses were clearly larger during the winter day, because the supply relied mainly on offshore wind power. Consequently, a huge amount of power is injected in only a few grid points and travels long distances to reach the loads spread across the entire country. The summer day presents the opposite scenario. PV systems are installed in almost all regions, meaning that the supply is more distributed and thus closer to the demand. Power flows have a lower volume and travel smaller distances, directly reducing active power losses.

For the same reasons, overloads in transmission lines and transformers are more common during the winter day, which is evident in Tables III and IV. Around offshore wind power connections, several 380-kV corridors exceed 75% loading (8 lines; max 6.25 h). Additionally, only 2 150-kV lines are affected, but they endure the longest overloading durations (up to 16.25 h). The afflicted lines are concentrated in *Gelderland*, *Flevoland*, and *Utrecht (GFU)*, where limited onshore wind



(a) Winter Day



(b) Summer Day

Fig. 3: Dispatch profiles for flexibility resources on winter and summer days.

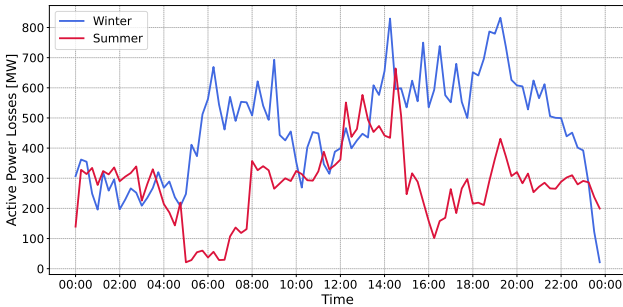


Fig. 4: Active power losses for winter and summer day. Total energy losses: 11.24 GWh (winter), 6.70 GWh (summer)

and significant battery activity shift flows across the subtransmission network.

TABLE III: Overloaded Transmission Lines by Voltage Level (Loading > 75%)

Day	Voltage Level	Overloaded Lines	Maximum Overload Duration (h)
Winter	150 kV	2	16.25
	380 kV	8	6.25
Summer	110 kV	2	3.50
	380 kV	2	1.50

Overloads are scarce during the summer day. The most critical region is the 110-kV network of *Groningen and Drenthe (GD)*. Here, solar power creates a very large surplus near midday, which saturates flexibility options in this region

TABLE IV: Overloaded Transformers by Voltage Level (Loading > 75%)

Day	Voltage Level	Overloaded Transformers	Maximum Overload Duration (h)
Winter	380/150 kV	2	5.50
Summer	220/110 kV	2	2.75

and flows to the 380/220-kV networks, and then towards other provinces.

Table V lists the largest deviations in bus voltage magnitude for each day. In winter, solar output is minimal and limited to a few hours; therefore, PV inverters have headroom to provide reactive power, keeping voltages well within bounds throughout the day. The lowest winter values occur in the 110-kV network of *Friesland (F)*, around 0.985-0.986 p.u. In summer, PV operates near rated active power for much of the day, reducing reactive capability; despite large-scale STATCOMs, the lowest voltages occur around midday in *Groningen and Drenthe (GD)*, approaching the 0.95 p.u. limit.

TABLE V: Largest Busbar Voltage Deviations on Each Day

Day	Busbar	Voltage Magnitude [p.u.]
Winter Day	F_low1	0.986
	F_low2	0.986
	F_low3	0.985
Summer Day	GD_low3	0.959
	GD_low4	0.957
	GD_low6	0.958

V. DISCUSSION

A. Spatial Aspects of Flexibility Deployment

In the summer scenario, decentralized resources such as residential batteries and distributed PV help reduce transmission loading. These units mitigate local voltage deviations and absorb midday solar surplus, minimizing long-distance power flows.

Conversely, the winter scenario highlights the limitations of centralized flexibility options under high offshore wind conditions. Batteries and electrolyzers located inland face curtailment or limited dispatch due to congestion on key 380-kV corridors. This suggests that, in addition to capacity, the geographical placement of flexibility must be considered to maximize its operational value.

B. System Stress and Control Implications

Although the analysis is based on steady-state calculations, the variation in system conditions throughout the day allows us to infer time-dependent operational stress patterns and control needs

Transmission congestion and voltage support requirements are more pronounced on the winter day. These conditions emerge despite total demand remaining comparable to the summer case, indicating that generation patterns and power flow directionality are the dominant stress drivers. Control

strategies such as coordinated charging of batteries, curtailment of electrolyzer demand, and the dynamic use of inverters for voltage support will be crucial for system stability.

Furthermore, although demand response offers valuable load-shaping potential, it remains insufficient on its own to alleviate stress during peak periods. This points to the need for a diversified flexibility portfolio and advanced grid-aware scheduling mechanisms.

C. Limitations and Modeling Assumptions

Only two representative days were simulated, omitting inter-day storage dynamics and forecast uncertainty. Flexible resources were modeled with ideal availability and fixed efficiencies. Sector coupling (e.g., heating or transport constraints) and market interactions are outside the scope of this study.

Capacity figures follow government and industry outlooks; if actual build-out is lower, utility-scale PV and electrolyzer capacities would decline. Fewer electrolyzers would raise winter offshore-to-inland transfers (increasing loading and losses), while less utility-scale PV would reduce renewable energy capture and steepen evening ramps.

Despite these limitations, the results provide a meaningful first-order assessment and a foundation for dynamic and stochastic extensions.

VI. CONCLUSION AND FUTURE WORK

This paper presented a time-series operational assessment of the Dutch power system in 2050, based on a synthetic transmission system model and realistic generation and demand projections. Sequences of steady-state power flow simulations were conducted every 15 minutes for typical summer and winter days, with dispatch determined using the MVMO algorithm.

Quantitatively, daily losses are 11.24 GWh during winter versus 6.70 GWh in summer. Winter records 8 overloaded 380-kV lines (max. duration of 6.25 h) and 2 at 150-kV (max. duration of 16.25 h), compared with only two lines per voltage level in summer (max. duration of 3.5 h); minimum bus voltages are 0.985–0.986 p.u. in winter and 0.957–0.959 p.u. during summer.

The results show that:

- Flexibility resources are essential to manage peak demand, balance variable renewable generation, and reduce active power losses.
- Distributed resources, especially batteries, are more effective in summer due to better alignment with solar generation and localized consumption.
- Winter operation is more challenging due to centralized offshore wind infeed, leading to higher congestion, transmission losses, and voltage support requirements.
- Strategic spatial deployment of flexibility and grid-aware control are key enablers for operational reliability.

Future work will extend the analysis to multi-day simulations with storage state tracking, investigate the effects of forecast uncertainty, and explore integration with other energy sectors (e.g., heat and gas). In addition, the role of market

mechanisms and cost optimization will be studied to better inform both operational and investment strategies.

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