Innovative: International Multi-disciplinary Journal of Applied Technology
(ISSN 2995-486X) VOLUME 4 ISSUE 9, 2026

# Impact of a Nuclear Power Plant on the Energy Balance and Load Coverage of Uzbekistan's Power System

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**Abstract:**

This study examines the effect of a nuclear power plant comprising two VVER-1000 units and two 55 MW RITM-200N units on Uzbekistan's power system. Official capacity statistics and explicitly modelled daily profiles are used to estimate annual energy output and load coverage under two solar and wind scenarios. With an assumed 7% auxiliary consumption and a 90% gross capacity factor, estimated annual output after operating auxiliary consumption is 15.47 TWh. Availability, capacity factor and power supplied to the grid are distinguished. Constant nuclear output reduces residual load but does not change its hourly increments. In the higher-renewables scenario, a 500 MW storage facility with 2 GWh of recoverable energy reduces renewable curtailment by 25.1%. An analytical check identifies charging power as the binding constraint. The results apply to the stated model conditions. Actual outage schedules, shutdown auxiliary demand and network constraints require a separate assessment.

**Keywords:** nuclear power plant, power system, energy balance, load coverage, capacity factor, energy storage, Uzbekistan.

## 1. Introduction

When a new power plant is connected, it is important to assess not only its annual output. It is also necessary to understand in which hours that electricity will be required and how the operation of the remaining plants will change. For a power system containing solar and wind generation, these questions are closely linked to the daily load profile.

According to the official results for 2025, Uzbekistan had 148 power plants with a total installed capacity of 25.797 GW. Thermal power plants and combined heat and power plants accounted for 17.551 GW. The capacity of hydroelectric power plants was 2.441 GW, that of solar power plants 3.930 GW and that of wind power plants 1.652 GW. A further 0.223 GW was attributed to captive plants [1]. These data characterise the generation mix at the end of 2025 and are adopted in this work as the initial statistical basis.

The study considers a nuclear power plant with a total electrical capacity of 2,110 MW. The design configuration comprises two VVER-1000 units and two RITM-200N units of 55 MW each. The main attention is given to the annual energy contribution of the plant and to the way its baseload operation changes the daily load imposed on the remaining sources. Contractual commissioning dates and the rated characteristics of any specific project are not established in this work.

## 2. Relevance and literature review

In an official statement of 28 January 2025, Uzbekistan's electricity demand for 2035 was estimated at 135 TWh [2]. This dated forecast is adopted as a reference value for the calculation rather than as guaranteed future consumption. A study by the German Economic Team contains a demand forecast and historical hourly data for 2014–2023 obtained from CDC Energiya [3]. These characterise the unevenness of the load but are not the source of the numerical weights of the model day used in the present work.

Mukhammadiev and Dzhuraev examine the justification of the energy and economic parameters of pumped storage hydroelectric power plants under the conditions of Uzbekistan [4]. The IAEA publication NG-T-3.8 addresses the interaction of nuclear power plants with the electrical grid [5], while NP-T-3.23 considers load-following and frequency-control modes of flexible operation [6]. International assessments treat nuclear generation as one component of secure low-carbon electricity supply [7], and system studies indicate that flexible nuclear operation can reduce the curtailment of variable renewable generation [8]. The constant nuclear output adopted in the present model does not imply that power regulation of the units is technically impossible.

According to the results for 2025, battery energy storage systems with a total capacity of 1.245 GW were commissioned in the country [1]. At the same time, the investment proposal for the Karateren pumped storage plant provides for a capacity of 500 MW [9]. The existence of such a proposal does not confirm that the pumped storage plant has entered operation. Existing battery systems and the pumped storage project are therefore treated separately.

Assessing a storage facility requires more than its power rating. The quantity of energy it is able to absorb and subsequently return to the grid must also be taken into account. Studies of systems with high shares of variable renewable generation show that curtailment and the required storage duration depend jointly on charging power and energy capacity [10], [11]. The present work uses a computational storage facility that is not tied to any specific site. Its energy capacity and efficiency are not confirmed characteristics of the Karateren plant.

In the textbook Power System Operations by Conejo and Baringo, power flow, the optimisation of operating regimes and unit commitment are treated separately [12]. A simpler balance model is used in the present work. It determines the capacity required from the remaining sources but does not verify which specific units would be able to provide it given network and operational constraints.

## 3. Problem statement

The purpose of the study is to assess the annual contribution of a 2,110 MW nuclear power plant and its effect on daily load coverage. Three regimes are compared for this purpose. The power system is first considered without nuclear generation, then with the nuclear plant in operation, after which a storage facility is added to the calculation.

A separate task is to determine the reason why the storage facility may be unable to absorb the entire daytime surplus of electricity. Such a result is possible both with insufficient energy capacity and with limited charging power. In order to distinguish these constraints, the numerical solution is verified against an analytical relationship. The study is performed for specified daily profiles and does not constitute a forecast of actual dispatch regimes.

## 4. Theoretical part and initial conditions

### 4.1. Capacity and annual electricity supply

The total rated capacity is obtained by summing the capacities of the four units and amounts to $2 \times 1{,}000 + 2 \times 55 = 2{,}110$ MW. In the calculation it is conventionally taken as gross capacity. After deduction of auxiliary consumption, the capacity supplied to the grid is determined by the expression

$$P_{net} = 2{,}110(1 - a) \quad (1)$$

where a denotes the share of auxiliary consumption and Pnet is expressed in MW. The value of a is taken to be identical for all units and constant during operation. This simplification does not reflect the differences between the auxiliary equipment of the VVER-1000 and RITM-200N units. If the design ratings are already defined as net capacities, auxiliary consumption must not be deducted a second time.

In the present calculation the capacity factor K is defined with respect to gross output. It equals the ratio of the electricity generated during the year to the output that would be produced by continuous operation at rated capacity. With a constant share of auxiliary consumption and a year of 8,760 hours, the calculated supply is

$$E_{NPP} = 8{,}760 \cdot K \cdot P_{net}/10^6 \quad (2)$$

where ENPP is expressed in TWh. For the sensitivity analysis, auxiliary consumption values of 5%, 7% and 10% are adopted. The coefficient K varies from 0.80 to 0.95 in steps of 0.05. These values are specified for the calculation and are not confirmed design characteristics. Expression (2) accounts for auxiliary consumption as a share of output but does not include the additional consumption arising during shutdowns.

### 4.2. Equipment availability and the treatment of outages

In the IAEA PRIS methodology, the indicators of actual generation, operating time and reference generation are treated separately. For the Load Factor indicator, consistent values of energy and net reference capacity are used [13]. Expression (2) adopts a different and explicitly stated order of accounting: the capacity factor is first specified with respect to gross output, after which the share of auxiliary consumption is deducted. A gross numerator must not be combined with a net denominator when statistical indicators are transferred.

The availability factor is not equivalent to the capacity factor. In definition 106 of GOST R 27.102-2021 it characterises the probability that an item is in an operable state, while planned periods during which use of the item for its intended purpose is not envisaged are excluded from consideration [14]. Availability can therefore not be taken, without clarification of its definition, as the share of all calendar hours of operation at full capacity. The standard is used here to clarify terminology and not as confirmation of the regulatory conformity of the project in Uzbekistan.

In the adopted value K = 0.90, outages and capacity reductions are represented in aggregate through the shortfall in generation. This coefficient is not derived from the calendar schedule of refuelling and maintenance outages. It must not additionally be multiplied by an availability factor without distinguishing the losses accounted for, since the same outages may otherwise be counted twice.

Refinement of the annual balance will require the capacity of each unit to be specified hour by hour, together with its auxiliary consumption both during operation and during shutdown. All station consumption within the selected accounting boundary should be deducted from total generation. Until such data are available, the result of expression (2) should be regarded as a preliminary estimate rather than as a complete annual balance of exchange with the grid.

### 4.3. Daily load and generation regime

The hourly calculation is performed with a one-hour step. The average load of the model day is normalised to the reference value of 135 TWh and equals 15.411 GW. The daily shape is specified by the weights wh given in Table 1. The load is determined as Lh = (135,000/8,760)wh/1.01. Division by the mean weight value of 1.01 preserves the specified average capacity. This normalisation does not imply that all days of the future year will have an identical profile.

Table 1. Weighting coefficients of the model daily profile

| Hour | Weight | Hour | Weight | Hour | Weight | Hour | Weight |
|---|---|---|---|---|---|---|---|
| **0** | 0.86 | 6 | 0.96 | 12 | 1.01 | 18 | 1.22 |
| **1** | 0.83 | 7 | 1.02 | 13 | 1.01 | 19 | 1.24 |
| **2** | 0.81 | 8 | 1.05 | 14 | 1.02 | 20 | 1.20 |
| **3** | 0.81 | 9 | 1.06 | 15 | 1.05 | 21 | 1.11 |
| **4** | 0.83 | 10 | 1.07 | 16 | 1.10 | 22 | 0.99 |
| **5** | 0.88 | 11 | 1.03 | 17 | 1.17 | 23 | 0.91 |

Two variants of installed renewable capacity are considered. In scenario M the capacity of solar power plants S is 10 GW and that of wind power plants W is 4 GW. In scenario H these values are increased to 16 and 8 GW respectively. Consumer load is identical in both cases. The abbreviations SPP and WPP are used hereafter for solar and wind power plants.

Solar generation is specified by the expression $PS,h = 0.85S \cdot \max\{0, \sin[\pi(h - 6)/12]\}$. Wind generation is constant and equal to PW,h = 0.35W. The hour h takes integer values from 0 to 23. The load shape and the availability of solar and wind capacity are selected for the model calculation. They do not reproduce measurements of any particular day and do not describe an approved plant construction plan.

On the day under consideration, all four nuclear units are conventionally in operation. Their constant net capacity PN equals 1.9623 GW at an auxiliary consumption of 7%. The annual capacity factor is not used to reduce the capacity in each hour. The daily calculation describes one operating regime rather than a full year including maintenance outages. A separate nuclear generation profile is required for days on which a unit is shut down. The initial profiles of scenario H are shown in Figure 1.

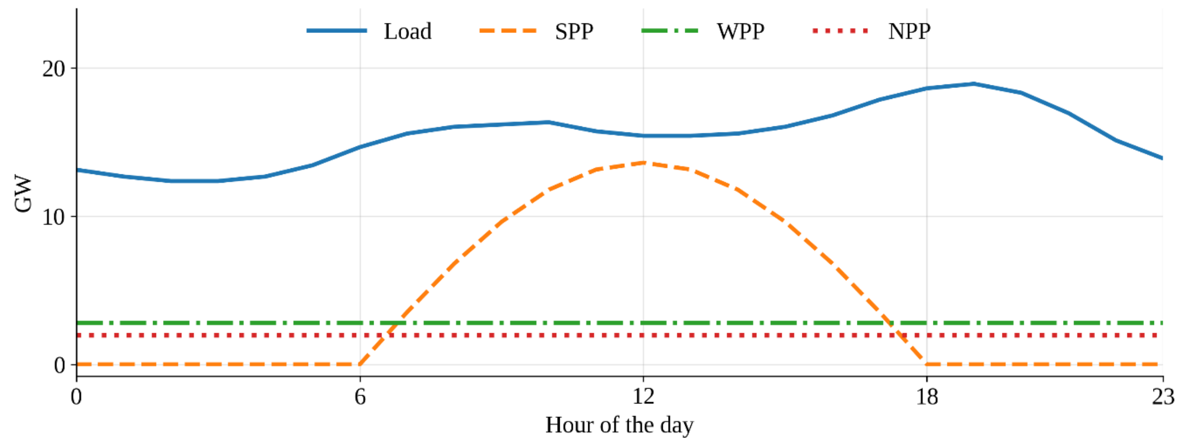


Figure 1. Calculated daily profiles of load and generation in scenario H

After deduction of solar, wind and nuclear generation, the load that must be covered by the remaining sources is obtained. It is determined by the expression

$$Rh = Lh - PS,h - PW,h - PN (3)$$

A positive value of Rh indicates a requirement for other generation. A negative value denotes a surplus of available capacity. Without storage, the required other generation equals Gh = max{Rh, 0} and the curtailment of solar and wind output equals Ch = max{−Rh, 0}. In this model the nuclear plant maintains a constant supply.

It follows from expression (3) that the constant capacity of the nuclear plant shifts the profile Rh downwards without changing the difference between its adjacent values. This statement applies specifically to the residual load before it is bounded below at zero. For Gh = max{Rh, 0} such invariance of the increments does not hold in the general case. The reduction of the evening maximum and the reduction of the ramp rate must therefore be assessed separately.

### 4.4. Storage operating conditions

Standard IEC 62933-2-1 addresses the parameters of energy storage systems and their testing methods [15]. IEC 62933-3-1 covers the planning, sizing, operation and performance assessment of grid-connected storage [16]. In the present model, power, energy capacity and efficiency are specified separately. Their numerical values are selected for the calculation and are not taken from these standards. Verification of the conformity of any specific installation with the IEC requirements is not performed.

The charging and discharging capacities of the storage facility are both taken as 0.5 GW. The limiting energy content X is 2 GWh and the round-trip efficiency η is 0.80. The stored quantity xh is understood as the energy that the facility is able to return to the grid. Under this definition, all cycle losses are accounted for during charging and are not deducted a second time during discharging.

The power balance and the change in stored energy are written as follows

$$Gh + dh - ch - Ch = Rh \qquad (4)$$

$$xh+1 = xh + \eta ch\Delta t - dh\Delta t \qquad (5)$$

Here ch and dh denote the charging and discharging powers in GW. The stored energy xh lies between zero and X and is expressed in GWh. At the beginning and at the end of the day it equals zero. The power in each mode does not exceed 0.5 GW, other generation cannot be negative, and curtailment does not exceed the available solar and wind generation.

Charging is permitted from hour 9 to hour 17 and only from the surplus $Q_h = \max\{-R_h, 0\}$. Discharging is permitted from hour 17 to hour 24. The starting hours of the charging intervals take values from 9 to 16 and those of the discharging intervals from 17 to 23. This separation excludes simultaneous charging and discharging.

The storage regime is determined by the sequential solution of linear programmes. Daily curtailment is minimised first. Among the solutions giving the same result, the one with the lowest maximum of other generation is then selected. Where these indicators are equal, preference is given to discharging in the hours of higher initial residual load, which corresponds to maximising the sum $\Sigma R_h d_h$.

The HiGHS solver was used for the numerical solution [17]. The hourly balances, the limiting values of power and stored energy, and the equality between the discharged energy and the product of the charged energy and the cycle efficiency were verified. The discrepancies were smaller than $10^{-6}$ in model units.

### 4.5. Verification of the power and capacity constraints

The quantity of energy that the storage facility will absorb from the grid can be verified without solving the optimisation problem again. For this purpose, a zero initial stored energy, the absence of discharging during the charging period J, and a sufficient opportunity to return the accumulated energy later are assumed. Then

$$E_{abs} = \min\{\Sigma_{h\in J} \min\{P_{ch}, Q_h\}\Delta t, X/\eta\} \qquad (6)$$

The first expression within the outer braces shows how much energy can be absorbed during the available hours at the specified charging power. The second defines the limiting quantity of incoming energy given the capacity and the losses. Actual absorption is limited by the smaller of these quantities.

This relationship follows from the hourly constraints. The sum in expression (6) gives the greatest energy available under limited charging power, while the quantity $X/\eta$ defines the limit imposed by capacity with losses taken into account. If the sum is smaller than $X/\eta$, increasing the capacity alone will not change the absorbed quantity. In the opposite case the capacity is binding. Attainment of the smaller bound presupposes that the accumulated energy can subsequently be returned to the grid in full.

## 5. Calculation results

### 5.1. Annual contribution of the nuclear power plant

At an auxiliary consumption of 7% and a capacity factor of 90% with respect to gross output, the calculated net capacity is 1,962.3 MW. The annual supply obtained from expression (2) equals 15.4708 TWh. Its ratio to the reference demand of 135 TWh is 11.46%. The indicator characterises the scale of the possible contribution of the plant. It is not a final share in supply to consumers, since consumption during shutdowns, network losses and the boundaries of demand accounting require clarification.

When auxiliary consumption and utilisation vary within the adopted limits, the annual supply ranges from 13.31 to 16.68 TWh. With unchanged demand, the corresponding share lies between 9.86% and 12.36%. This is a range of calculated variants and not a confidence interval or a probabilistic forecast.

### 5.2. Daily load coverage

In scenario M no surplus of electricity arises. After the nuclear plant is connected, the daily generation required from the remaining sources decreases from 271.699 to 224.604 GWh. Under the adopted condition of charging only from surplus, the storage facility does not operate. This follows from the rules of the present calculation and does not mean that storage cannot be used for other purposes.

In scenario H a daytime surplus appears even without nuclear generation. With the nuclear plant in operation it increases, although the evening requirement for other sources declines. Daily curtailment of solar and wind output rises from 1.735 to 8.813 GWh. At the same time the maximum required other generation decreases from 16.120 to 14.158 GW. The results of the comparison are presented in Table 2.

Table 2. Load coverage indicators for the model day

| Scenario and regime | Maximum G, GW | Energy G, GWh | Curtailment, GWh |
|---|---|---|---|
| **M without NPP** | 17.520 | 271.699 | 0.000 |
| **M with NPP** | 15.558 | 224.604 | 0.000 |
| **H without NPP** | 16.120 | 201.096 | 1.735 |
| **H with NPP** | 14.158 | 161.078 | 8.813 |
| **H with NPP and storage** | 13.658 | 159.307 | 6.599 |

In the table, G denotes the required other generation. All values are obtained with the same load profile. Curtailment refers only to the available output of solar and wind power plants.

In scenario H the nuclear plant supplies 47.095 GWh over the day, whereas the output of other sources decreases by only 40.018 GWh. The difference is due to the additional curtailment of solar and wind generation. Consequently, the entire supply from the nuclear plant cannot automatically be equated with the reduction in output of other dispatchable plants. The result depends on the hours in which the electricity enters the grid.

### 5.3. Effect of the storage facility

In scenario H the storage facility absorbs 2.214 GWh and returns 1.771 GWh to the grid. The round-trip losses amount to 0.443 GWh. Curtailment decreases from 8.813 to 6.599 GWh, that is by 25.12%. The maximum required other generation falls by a further 0.500 GW to 13.658 GW. The change in the profiles is shown in Figure 2.

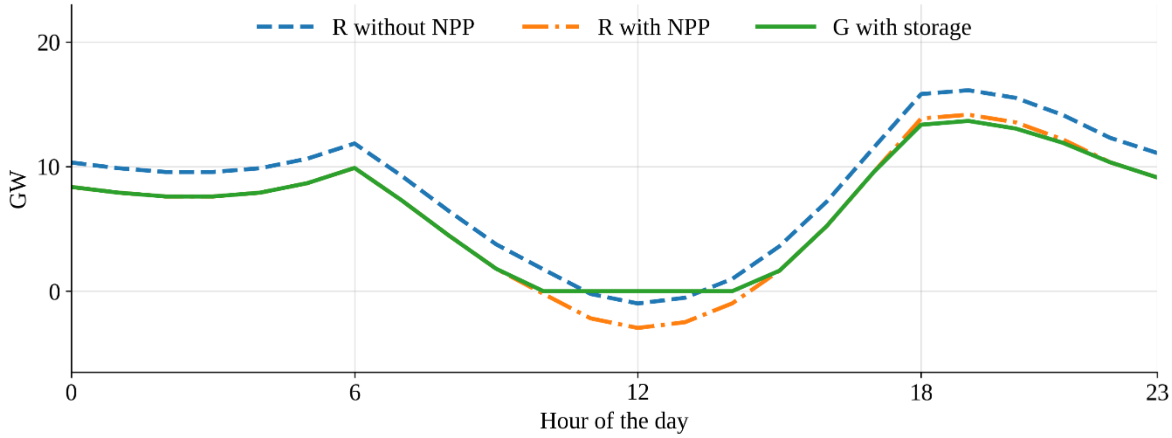


Figure 2. Residual load and other generation in scenario H

The storage facility is nevertheless not filled completely. The greatest quantity of returnable energy is 1.771 GWh against the permissible 2 GWh. According to expression (6), 2.214 GWh can be absorbed through the charging equipment, whereas the capacity would permit $X/\eta = 2.500$ GWh. On this day, therefore, it is precisely the 500 MW power rating that limits the charged quantity. Increasing the energy capacity without changing the power rating will not improve the result.

Seven hours are available for the subsequent discharge. At a power of 0.5 GW, up to 3.5 GWh could be returned during this time, which exceeds the 1.771 GWh actually accumulated. The evening discharge window therefore does not impede the use of the absorbed energy in this case. The analytical check and the numerical solution give the same result.

In order to absorb the entire surplus of scenario H without daytime discharging, the charging power would have to be no lower than 2.951 GW and the returnable energy content no lower than 7.050 GWh. These are necessary bounds and not optimal project parameters. If the discharging power of 0.5 GW is retained, a seven-hour evening window will permit no more than 3.5 GWh to be returned. A complete daily cycle would therefore also require a higher discharging power or a longer discharge window.

The greatest hourly increase in the initial residual load in scenario H is 4.348 GW/h both without the nuclear plant and with its constant output. In the selected solution, the storage facility reduces the evening maximum of other generation but does not reduce its greatest hourly increase. This is a consequence of the specified dispatch: the objective function minimises curtailment and peak capacity rather than the rate of change of load.

## 6. Practical significance and limitations

Expression (6) makes it possible to establish in advance which storage parameter limits the use of the surplus. This helps to avoid a situation in which an increase in energy capacity is regarded as a sufficient solution although the charging equipment is unable to absorb the available energy. The check should be repeated for different daily profiles, since the binding factor may change.

In the daily model, thermal and hydraulic plants are combined into the single indicator of other generation. Their minimum loads, ramp rates and the availability of individual units are not specified. External flows and network losses are taken as zero. Seasonality, calendar maintenance outages, renewable forecast errors and reserve provision are not modelled. The annual capacity factor reflects the generation shortfall in aggregate and does not substitute for these constraints.

The calculated requirement for other generation therefore does not yet demonstrate that the existing plants would be able to provide such a regime. Daily curtailment cannot be extrapolated to the year. The next level of verification should include an hourly series for a full year together with the constraints of individual units [12]. Coordination of nuclear plant outages with the system operator and verification of post-contingency regimes belong to the separate tasks of plant–system interaction [5].

**7. Conclusions**

For the configuration considered, a nuclear power plant of 2,110 MW with an auxiliary consumption of 7% and a capacity factor of 90% with respect to gross output yields a calculated annual supply of 15.47 TWh. Its ratio to the adopted reference demand of 135 TWh is 11.46%. Auxiliary consumption during shutdowns and actual maintenance schedules must be taken into account in moving from this estimate to a complete annual balance.

Constant nuclear generation reduces the level of the residual load but does not change its hourly increments. In the variant considered with high solar and wind capacity, the reduction in the evening requirement for other sources is accompanied by an increase in the daytime surplus. This result depends on the selected profiles and on the unchanged nuclear regime.

A storage facility of 500 MW with an energy capacity of 2 GWh reduces curtailment by 25.1% on the day considered. Its capability is limited by charging power, although part of the energy capacity remains unused. This result is confirmed both by the numerical solution and by the analytical relationship.

The joint operation of nuclear plants and storage should be assessed simultaneously in terms of annual energy and the hourly balance. The availability factor, the capacity factor, auxiliary consumption and storage parameters address different questions and cannot substitute for one another. The results obtained provide a verifiable estimate for the specified conditions but do not replace the assessment of capacity adequacy, reserves and power system stability.

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