

# Resource modeling to provide the “flexibility” of the power system in its low-carbon redevelopment

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**Abstract.** Initiatives to combat climate change imply the decarbonization of the economy. Transport and energy are the most promising sectors in terms of decarbonization's technological feasibility. However, the decarbonization of these sectors may cause several problems in terms of the sustainability of the energy system. This is because electric transport creates additional atypical demand in the energy system, while non-carbon energy sources such as nuclear power plants and renewable energy sources have generation limited by maneuverability characteristics or weather conditions. To avoid significant consequences from imbalances between demand and supply, before implementing decarbonization projects, it is necessary to conduct modeling of the energy system's flexibility. Solving such a task requires specialized modeling tools - optimization models of intra-annual commercial dispatching of generating and storage capacities. This article addresses critical requirements for a modeling tool, various applicable modeling approaches, and software options. The article also presents the results of modeling the conditions for balancing supply and demand in the UES of Russia at the level of 2050, considering a high level of transportation electrification and covering additional demand through various generation technologies, including carbon-neutral ones.

## 1 Introduction

In the context of global initiatives to combat climate change, such as the Paris Agreement [1], most countries around the world are focusing their attention on the decarbonization of their economies. Particular emphasis is placed on the energy sector, particularly the electricity industry. This is due to the unique technological capabilities of the industry in the use of various types of carbon-free resources as an alternative to traditional fossil fuels.

According to the International Energy Agency (IEA), the share of non-carbon sources in the total electricity production has increased by almost 3.5 times over the past 50 years [2], mainly due to an increase in the capacity of nuclear power plants (NPP) and renewable energy sources (RES).

For Russia, the task of decarbonizing the economy is also on the agenda. The President has outlined a long-term goal to achieve carbon neutrality by 2060 [3], and therefore, as part of the country's Development Strategy until 2050 with low greenhouse gas emissions, the Government of the Russian Federation [4] plans to significantly increase the capacity of carbon-free generation [5].

Within the framework of the Unified Energy System of Russia (UES), carbon-free power plants, primarily hydroelectric power plants (HPP) and nuclear power plants account for about 32% of installed capacity, providing 36% [6] of total electricity generation. At the same time, by 2035 it is planned to commission 12.2

GW of new NPP power units, 6.7 GW of new HPPs, and pumped storage power plants (PSPP) [5].

Unlike most European countries, the development of wind and solar energy in Russia is relatively small, despite the support measures taken by the government [7], the share of renewable energy is about 2.4% of the total installed capacity [8].

In addition to the energy sector, various countries, including Russia [9], are planning or already implementing substantial efforts towards decarbonization in other sectors, particularly the transportation sector, which also holds significant potential for replacing organic fuels with electric power [10] or hydrogen (a resource often produced using electric power).

As the use of carbon-free energy sources such as RES and NPPs increases, and more consumers switch to electricity, there is a need to adapt energy systems to cope with the growing imbalance between the changing daily profiles of electricity consumption and generation. This challenge is further amplified by the increasingly stochastic nature of electricity generation due to the impact of RES [11].

The adaptability of an energy system to such imbalances is often referred to as "flexibility" and can be ensured by having sufficient resources for reserving or rapidly adjusting both production and consumption loads.

Various solutions with varying degrees of complexity, effectiveness, and cost have been successfully implemented, contributing to the integration

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of significant amounts of carbon-neutral energy generation in different energy systems. For instance, Denmark has implemented such solutions in parallel energy systems, Ireland in isolated energy systems, and King Island in Australia in small island systems [12, 13].

These solutions encompass geographic distribution of RES generation, restructuring markets for flexibility rewards, enhancing grid infrastructure, deploying advanced battery technologies, developing demand-side management programs, and much more [14].

Many of the aforementioned solutions do not require significant investments and can be considered as initial steps to unlock the potential of the energy system. However, for further progress toward achieving energy transition goals, it is crucial to take a comprehensive approach that weighs the costs of implementation against the achievable benefits of increased flexibility.

Early and long-term planning of the energy system development in the context of a low-carbon transition is necessary to avoid the implementation of costly urgent solutions when flexibility issues arise. For instance, a small system with limited maneuverable capacity and a high proportion of outdated equipment might experience flexibility shortages even with very low shares of NPP or RES, while a larger and more flexible system might encounter these challenges much later. In addition to the size of the power system, the structure and condition of existing capacity, the choice of future potential measures to increase the flexibility of the power system can also be influenced by the prospects for future growth in demand.

In several large energy systems, including the Russian Unified Energy System (UES) [15], a significant excess of capacity persists, many of which have limited maneuverability due to equipment conditions or co-generation of electricity and heat.

On the other hand, in larger energy systems, many thermal power plants have likely reached their payback periods, while newly constructed capacities in energy systems with rapidly growing demand might still have a considerable path to achieving profitability.

In newly established or fast-growing systems, it is usually easier to plan for flexibility as investments can be incorporated into market mechanisms and plans for introducing new generating and network capacities, instead of expensive upgrades to existing power plants and grid infrastructure [16].

Flexibility planning is a complex multi-stage process that requires consideration of a multitude of diverse factors and the solution of intricate mathematical problems.

## **2 Methods and tools for assessing energy system flexibility**

Modeling is based on the creation of formalized models, which are simplified but still representative descriptions of reality. Modeling is widely used in scientific research to analyze complex phenomena and systems, as well as to facilitate decision-making under uncertainty. Energy

systems are one of the traditional areas of application of various modeling methods.

Energy planning entails the use of mathematical methods, primarily optimization, and corresponding software to study the development and operation of energy systems. The results of energy modeling are indispensable for quantitatively justifying strategic decisions when formulating and implementing energy policies and programs, including in the context of low-carbon economic and energy transitions.

In modern energy planning practices, the study of the flexibility potential of an energy system and the assessment of the necessary measures are integral components of rationalizing the structure of generating capacities and prioritizing directions for technological upgrades in the power sector, particularly regarding decarbonization requirements.

Addressing such a task requires a specialized modeling tool that simulates the process of commercial dispatch of energy and meets several general requirements:

- The capability for co-modeling the functioning of various segments of the energy system (generation, consumption, inter-system energy flows, etc.),
- Sufficiently high levels of technological and temporal detailing for objective modeling of different energy technologies and their interactions,
- An adequate modeling horizon, spanning at least a year, to capture intra-annual (seasonal, weekly, daily, etc.) variations in consumer load profiles and the dispatch capabilities of various types of power plants,
- The ability to search for economically optimal solutions and analyze price-related implications

The last requirement is especially important to ensure that proposed solutions are justified from both technical and economic standpoints. Measures to enhance energy system flexibility during its low-carbon transformation are part of a comprehensive investment plan for altering the structure of generating capacities and developing the electrical grid. The task before experts is not to achieve maximum flexibility at any cost. On the contrary, given a predefined capacity development plan, it's necessary to determine a reasonable scale of flexibility enhancement and propose the least costly measures for achieving it. Moreover, the assessment of the cost of adapting the energy system to the new capacity structure could lead to adjustments in the initial plan of changing the generation capacity structure.

When exploring the flexibility potential of a power system, it's important to assess the price implications. This is especially true in a working classical competitive electricity market where pricing is based on the marginal short-term variable costs of suppliers. The intensive development of non-carbon generation with different intra-annual modes of power use significantly distorts the profile of the supply curve [11] and changes the levels of equilibrium prices (up to zero or negative values in some hours). The use of linear models of commercial dispatching with minimization of electricity production costs makes it possible to study the change in the spot price profile based on the solution of a dual linear programming problem. The shadow prices of the

balance equations formed in the dual problem reflect the cost of producing an additional MWh of electricity over a given demand, that is, the spot price.

Existing tools and methods for flexibility assessment in global practice are intended for various purposes, ranging from visual comparisons to operational planning of energy systems of varying complexity. Simpler tools can be utilized for preliminary risk analysis of insufficient energy system flexibility in regions and countries lacking powerful computational tools required for detailed studies of renewable energy integration. They also serve to enhance the awareness of individuals involved in making strategic decisions and motivate a more detailed analysis of the problem. More complex and comprehensive tools can be employed for large-scale studies on the low-carbon transformation of energy systems, including their economic component (determining total costs, required revenue, and the impact on competitive price profiles).

Based on the complexity of the task and the level of detail (technological, regional, temporal, etc.), existing flexibility assessment approaches outlined in the literature [17] can be categorized into three levels:

- Level 1: Tools with minimal requirements for input data, for example, without time series. They can be based on data about generation structure, inter-system connections, and other potential flexibility sources and usually require expert assessment. A qualitative assessment can provide a quick comparison of different options for changes in the energy system structure and give recommendations for priority steps to enhance its flexibility. Such tools can be useful for understanding the depth of potential operational problems, but they won't provide much quantitative information for specific investment plans and projects.

- Level 2: Tools that assess a sufficient level of flexibility based on time series and more detailed individual data, usually with calculations performed without full optimization of the energy system's operation over the considered period. Time series (e.g., demand and generation, which must be synchronized with each other) are formed based on historical data and/or meteorological sources and transformed for future use. The modeling results can indicate when and to what extent additional flexibility may be required to avoid forced curtailment of RES, power shortages, or other undesirable phenomena.

- Level 3: Tools based on optimization models of power dispatch (possibly used in combination with models of investment planning for generation and network capacities). Third-level models are widely used in the operational management and planning of energy systems. Therefore, they provide the most detailed techno-economic basis for analyzing the sufficiency of flexibility. However, such models are often complex tools requiring vast amounts of input information. The quality of model solutions critically depends on the level of expertise and experience of researchers. Many of these models were developed for other purposes, and hence most of them require subsequent processing of results for flexibility analysis.

Based on this classification, Table 1 provides a brief overview of several tools and methodologies that can be used for flexibility assessment, along with their typical characteristics and limitations.

Among the considered tools, the most effective (but also difficult to use) are optimization models for intra-annual commercial dispatch of generation and storage capacities. One such model, called FlexTool, has been developed by the International Renewable Energy Agency (IRENA).

FlexTool is a linear optimization model that mathematically formalizes the real-world problem of optimizing hourly energy dispatch (including investment planning). In this model, the objective function and constraints have linear dependencies on variables. The model aims to find variable values that minimize the objective function (costs) while adhering to constraints defined by linear equations or inequalities.

This tool is currently being integrated into the ERI RAS SCANNER model-information complex [18]. Input scenarios for changes in the generation structure (including potential emissions constraints from power plants and boilers, carbon pricing, and other carbon regulatory measures) are formed using another tool developed at ESI RAS, the Energy and Power Optimization Model (EPOS). Solutions obtained from EPOS (power structure determined through economic optimization over a significantly longer horizon than FlexTool) are tested for flexibility compliance for each hour using dispatch modeling.

FlexTool is capable of modeling systems of any size, provided that input data is sufficiently aggregated. Also, a significant advantage of FlexTool is that it has an open-source code, allowing users to understand its assumptions and operational principles, leading to more informed conclusions drawn from the obtained data.

### **3 Modeling the flexibility of the UES of Russia, taking into account the efforts to decarbonize the energy and transport sectors of the economy**

As an example of flexibility modeling, five scenarios for the development of the UES of Russia for 2050 were modeled to assess the adaptability of the forecast structure of generating capacities to changing modes of power consumption due to the development of electric transport. In the considered scenarios, the basic demand (without electric transport) by 2050 will increase by 378.5 billion kWh or by 36% compared to the year 2020. At the same time, scenarios 2-5 provided for additional demand caused by the electrification of transport in the amount of 167.7 billion kWh or 10.5% of total demand. The scenarios considered various options to meet additional demand:

- In Scenario 1, the structure of installed capacity optimized in the EPOS model provides the predicted demand without the additional influence of electric transport.

**Table 1.** Methods and tools for assessing the flexibility of the energy system [17].

	Approach	Software	Brief description	Requirements and restrictions
Level 1	Expert review	NREL System Evaluation Tool	Provides a basis for evaluating characteristics that are important in terms of flexibility	Experience is required to evaluate power systems in terms of flexibility. Not based on evidence
	Visual comparison	GIVAR (IEA)	Provides a snapshot of the current situation with relevant information about system resilience.	Based on a limited set of data. Can only give a qualitative assessment
Level 2	Manoeuvrability valuation	FAST2 (IEA), IRRE	Simulates the dispatching of the system in an hourly manner. In case of an insufficient level of flexibility, it informs about the impossibility of changing the load according to the specified parameters	The main attention is paid to the increase (growth) of capacity and reserves
	Operational uncertainty	InFLEXion (EPRI)	Uses scheduling simulation results and historical data to assess potential weaknesses in flexibility in various situations	Post-processing tool. Preliminary calculations and results of the dispatching model are required
	Flexibility test	Flex Assessment (EDF), REFLEX (E3)	Assesses the need for flexibility within an hour during the planning phase. Ability to account for variables, operating constraints, and additional reserves	Pre-optimization tool. Requires a separate power system planning and generation balancing model
Level 3	Reserve valuation	FESTIV (NREL)	Tool for dispatching (operational) balancing of scenarios with a high share of RES in a relatively short time frame (from seconds to a day)	High level of detail. Doesn't optimize the capacity expansion plan, only operational management.
	System planning and operational modeling	REFLEX (NREL), RESOLVE (E3)	A tool for optimal scheduling, while taking into account operational constraints that are relevant in terms of flexibility. It also allows you to solve the problem of capacity expansion planning at the lowest cost.	REFLEX optimizes the scenario with a valley-filling algorithm, which can lead to inaccuracies.
	System planning and operational modeling	IRENA FlexTool	A tool for optimal capacity dispatching and/or for optimizing investment decisions can be used to determine whether a power system is sufficiently flexible and how to increase it	Plant characteristics, networks, and time series are required. Only linear optimization.

- In Scenario 2, the structure of installed capacity is optimized using the EPOS model, while demand is increased taking into account the electrification of transport.

- In Scenario 3, the additional demand for energy and capacity, caused by the electrification of transport, is provided exclusively by combined cycle gas turbines (CCGT).

- In Scenario 4, the additional demand is provided only by NPP.

- In Scenario 5, the additional demand is provided only by RES.

Detailed scenarios and assumptions are described in Article [19]. Table 2 reflects the aggregated types of

power plants, their capacities, and average annual capacity utilization factors (CUFs), obtained through hourly aggregation. Changes in power plant CUFs and the extent of energy storage utilization, make it possible to obtain an integral characteristic of the flexibility level. Notably, changes in the CUFs of thermal power plants help determine shifts in their capacity utilization patterns as the share of non-carbon generation increases. Other characteristics of the scenarios are changes in annual CO<sub>2</sub> emissions, total costs of ensuring balance, as well as changes in the weighted average spot price of electricity.

**Table 2.** Analysis results [19].

Scenarios	1		2		3		4		5	
	Capacity utilization factor, %/ Capacity, GW									
Thermal power plants	58.87	150,7	59.00	171,3	58.13	183,9	51.00	150,7	65.46	150,7
Wind power plants	27.97	15,7	27.97	15,6	27.97	15,7	27.97	15,7	27.97	37,3
Solar power plants	19.76	5,4	19.81	6,8	19.76	5,4	19.76	5,4	19.39	17,1
Nuclear power plants	90.85	42,1	90.85	48,2	90.85	42,1	90.72	75,3	90.85	42,1
Hydropower plants	44.04	50,2	42.49	52,1	44.04	50,2	44.04	50,2	44.04	50,2
Energy storages	13.67	2,5	25.63	5,7	33.82	2,5	36.9	2,5	33.03	2,5
	Change relative to 1 scenario, %									
Annual total costs to ensure the balance of electricity (the value of the objective function of the model)	0.00		12.04		15.49		-8.60		12.88	
Annual CO <sub>2</sub> emissions	0.00		12.55		13.51		-13.20		12.37	
Weighted average spot price of electricity	0.00		0.18		-7.72		-14.17		15.50	

Scenario 1 is considered a reference scenario, where no additional growth in demand due to electric vehicles is foreseen. The primary source of "flexibility" in this scenario is HPP, whose generation throughout the day varies by a factor of 2.8. Thermal power plants (TPP) and energy storages also contribute to balancing the demand and generation but to a lesser extent. Energy storage units are charged during nighttime hours when electricity demand is minimal, thereby leveling the demand curve during the hours of the night dip. Discharge from energy storage units occurs during daytime and evening peak hours when electricity prices are at their maximum and the use of storage is economically justified. Similarly, with varying degrees of intensity, energy storage units' function in the other examined scenarios.

In scenarios with increased electrification of transportation, the total electricity demand by 2050 will grow by 10.5%, and the overall installed capacity of power plants will increase by 12.5%. The calculated parameters of scenarios 2 to 5 are compared with scenario 1.

In Scenario 2, the additional electricity demand is met through a combination of different types of power plants (thermal, nuclear, hydro, and renewable), based on the results of optimizing the capacity structure, which closely resembles the parameters of Scenario 1. Consequently, the overall costs of maintaining the electricity balance in Scenario 2 increase proportionally to the rise in demand relative to Scenario 1. Minor adjustments in the capacity structure also signify that the spot market supply curve and the market equilibrium point will closely align with Scenario 1. This assertion is supported by a marginal difference (0.2%) in the level of the average weighted spot electricity price. A change in

the load profile due to electric transport will require more intensive use of storage devices - their storage capacity factor will increase by 12%, with a slight decrease in the HPP capacity factor by 1.5%.

In Scenario 3, where the additional demand is only by CCGT (with the capacity of all other types of power plants held constant at the level of Scenario 1), the higher fuel consumption leads to an increase in the cost of maintaining the electricity balance. This increase is higher than the demand growth itself, reaching 15.5% compared to Scenario 1. This scenario is characterized by the highest volume of CO<sub>2</sub> emissions. In this case, gas-fired power plants with lower specific fuel consumption partially replace less efficient stations in the balance, contributing to a certain reduction in the average weighted electricity price. In terms of flexibility, this scenario doesn't pose significant issues as CCGTs are among the most maneuverable energy sources with minimal operational limitations.

In Scenario 4, an intensive growth in the volume of electricity from NPPs displaces TPPs from the balance, which, in particular, can be seen from the decrease in their capacity factor in Table 2. To balance the low maneuverability of NPP, energy storages were more intensively utilized. Despite the increase in electricity consumption, both CO<sub>2</sub> emissions and the overall costs of maintaining the electricity balance decreased (by 8.7%). However, the most notable reduction occurs in the average weighted electricity price (by 14.2%). It's important to consider the conditional positive effect of reducing the spot price, as higher capacity payments might be necessary to ensure the financial viability of investments in new capacity (including NPP), leading to a substantial increase in the single tariff electricity price.

The last Scenario 5 assumes that the growth in demand is covered by RES. Model calculations revealed that this scenario places the highest demands on the energy system's flexibility. Due to the non-guaranteed generation of wind and solar power plants during certain hours, there are unacceptable reductions in reserves, and significant curtailment of RES generation occurs according to the balance conditions. In this variant, due to the low-capacity utilization factors of RES power plants, the forced solution is additional electricity generation from TPPs (with an increased capacity factor, as indicated in Table 2). Modeling this scenario showed an increase in the costs of maintaining the electricity balance, and a rise in the average weighted electricity price, and also revealed undesirable phenomena in terms of system flexibility, reflected in Figure 1.

### 4 Conclusions

Energy planning and flexibility modeling are essential components of finding an optimal combination of resources and technologies to meet energy demand sustainably, affordably, and reliably. Environmental considerations play an increasingly significant role, driving the transition towards a low-carbon technological structure in the energy sector, the replacement of fossil fuels with non-carbon sources, and electrification in end-use sectors, particularly transportation. Integrating large volumes of non-carbon sources and the emergence of new types of electricity consumers may require additional measures to enhance energy system flexibility. Special models of commercial dispatch are

employed for investigating this need, typically with detailed intra-annual granularity and economic optimization criteria. The dual problem solution of linear optimization models allows the exploration of changes in the spot electricity price profile.

An analysis of the functioning of the UES of Russia on the horizon up to 2050, performed using the FlexTool linear optimization model, showed that electric vehicles are a fairly powerful factor influencing both the volume of demand and the requirements for flexibility of the UES of Russia. Scaling up the optimal structure of generating capacity to meet higher demand allows achieving it with comparable growth rates in total costs for maintaining the electricity balance and minimal changes in the average weighted price. Furthermore, the energy system possesses sufficient flexibility reserves to maneuver the capacities of power plants and storage systems.

From an economic and environmental standpoint, the most efficient scenario involves covering the additional electricity demand primarily through NPP. However, this scenario requires further development of storage systems, including pumped storage power plants. An alternative scenario based on a predominant expansion of renewable energy sources (RES) could lead to substantial increases in the overall costs for maintaining the electricity balance, a rise in the average weighted electricity price, and exhibit inadequate energy system flexibility, necessitating significant enhancement of maneuvering capabilities both in generation and among consumers.

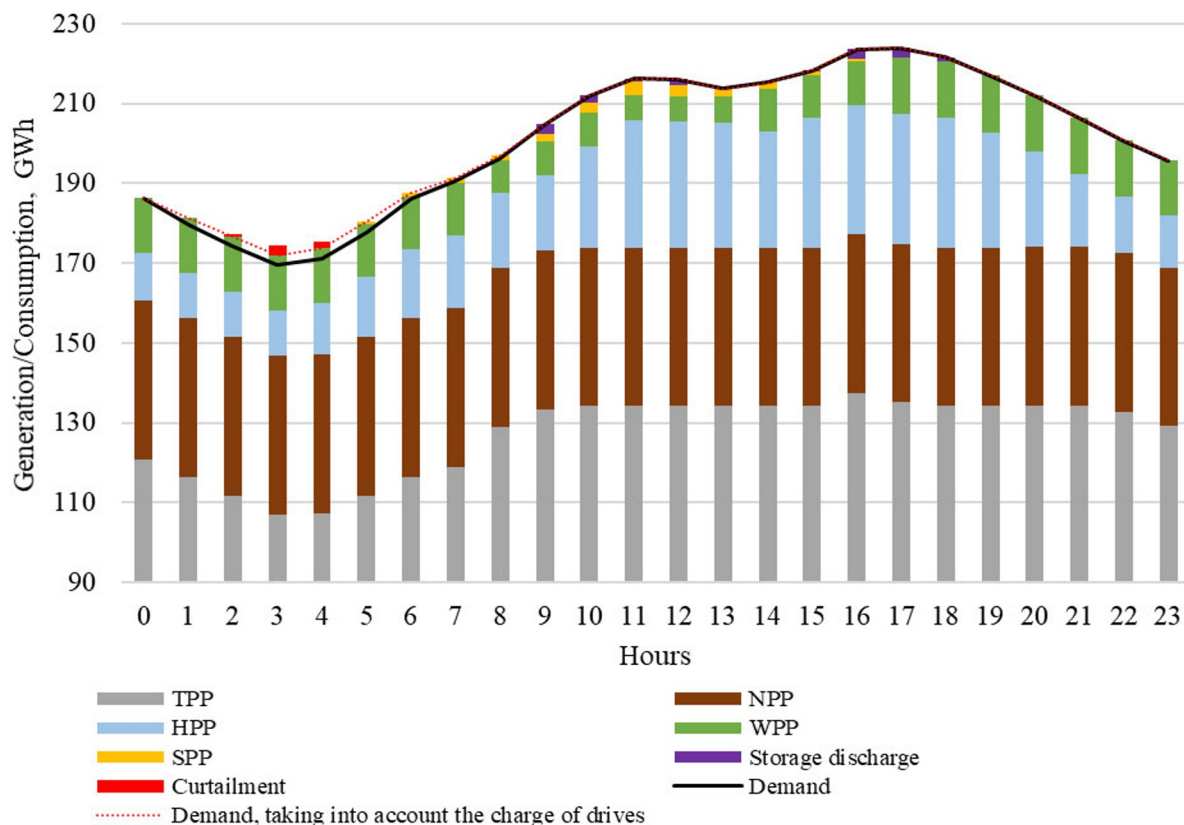


Fig. 1. Hourly electricity generation in 2050 for winter working day conditions (Scenario 5) [19].

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