NATIONAL TECHNICAL UNIVERSITY OF UKRAINE “IGOR SIKORSKY KYIV POLYTECHNICAL INSTITUTE”

Educational and scientific Institute of Energy Saving and Energy Management

(full name of the institute)

Electricity supply systems for consumers

(full name of the department)

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“Accepted to the defense”

Acting Head of the Department

__________ Denys DEREVIANKO

“___” _____________ 2022

Master’s thesis

under the specialty: 141 Electrical Energetics, Electrical Engineering and Electromechanics

Educational and Professional Program: Engineering of systems for providing consumers with electric energy

on the topic: “Improving the reliability of the energy system by using market-based mechanisms of influence on consumers”

Completed by: Master student (2d year), group OE-01mn

__________Dudko Kyrylo______________________ ____________

(Full name) (Signature)

Research Advisor _Ph.D., Assoc.Prof. Zamulko Anatolii_ ___________

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Consultant *norm control*, Asst. Prokopenko Iryna _______ __________

(section name) (Scientific degree, academic title, full name) (Signature)

Reviewer _______Professor Konrad Świrski________ __________

(Scientific degree, academic title, full name) (Signature)

I declare that this Master's thesis does not include any borrowings from the works of other authors without corresponding references.

Student _____________

(Signature)

Kyiv, 2022

NATIONAL TECHNICAL UNIVERSITY OF UKRAINE “IGOR SIKORSKY KYIV POLYTECHNICAL INSTITUTE”

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Specialty: 141 Electrical Energetics, Electrical Engineering and Electromechanics
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Acting Head of the Department
__________ Denys DEREVIANKO
“___” _____________ 2022

TASK
on the Master’s thesis research to student
Kyrylo DUDKO

1. Topic of the Master’s thesis: “Improving the reliability of the energy system by using market-based mechanisms of influence on consumers”

Research advisor: Ph.D., Assoc. Prof. Zamulko Anatolii_____________

approved by the university order dated on «27» April 2022 № HC/119/2022

2. Deadline for the Master’s thesis submission by student: «10» June 2022
3. Object of research: Operating modes and features of electrical networks
4. Subject of research: Methods and means of organizing market influence on electricity consumers to increase the efficiency of the UES of Ukraine
5. List of the tasks that have to be performed:

-to do comprehensive analysis of electricity demand management equipment capabilities in UES of Ukraine,
-Analyze market segment capabilities to ensure balancing in UES of Ukraine,
-to develop methodological principles for consumer analysis,
-to develop approaches to interruption tariffs to increase the reliability of UES of Ukraine

6. List of the graphical (illustrative) material: presentation - visual materials on the study results, calculation algorithms and tables with the results obtained.
7. Indicative list of publications: Derevianko D.G., Gilevich K.M., Dudko K.D. “Lightning protection of ground SES” / Collection of scientific works, 2020. - (Kyiv, November 26-27, 2020) -P.49-55;

8. Consultants for different sections of the Master's thesis:
Norm control, Asst. Prokopenko Iryna
9. Date, when the task was issued: 30 January 2022

Calendar plan

№	Name of the stage of the Master's thesis implementation	Terms of implementation	Notes
1.	Identification the purpose of research, object and subject of research	11.03.2022-18.03.2022	
2.	Identification the preliminary structure of the Master's thesis	19.03.2022-25.03.2022	
3.	Literature review and work on the first section of the Master's thesis	26.03.2020-02.04.2022	
4.	Literature review and work on the second section of the Master's thesis	03.04.2022-15.04.2022	
5.	Literature review and work on the third section of the Master's thesis	16.04.2022-15.05.2022	
6.	Literature review and work on the fourth section of the Master's thesis	16.05.2022-08.06.2022	
7.	Formatting the text of the Master's thesis	09.06.2022-13.06.2022	
8.	Preparing the Abstract and PowerPoint Presentation of the Master's thesis; receiving an official protocol of plagiarism detection results and peer review	10.06.2022-12.06.2022	
9.	Preliminary Master's thesis defense	13.06.2022	
10.	Master's thesis defense	15.06.2022	

Student _________ Kyrylo DUDKO

Research Advisor _________ Anatolii ZAMULKO

ABSTRACT

Structure and scope of work. The Master's thesis on the topic "Improving the reliability of the energy system by using market-based mechanisms of influence on consumers" consists of an introduction, 4 sections, conclusions, and list of references. The total volume of work is 113 pages, including 16 figures, 13 tables and 31 bibliographic references, 3 annexes on the 12 pages.

Relevance of research. The UES of Ukraine cannot solve management issues on its own, so involving the consumer in solving this problem is one of such important functions. The task of maintaining a high level of reliability or eliminating power shortages in the power system has been relevant for the UES of Ukraine for many years. Today, reliable operation of the Unified Power System (UES) of Ukraine is not possible without the use of modern means of frequency and active power control. Such regulation can be carried out both by controlling the generation by means of automatic frequency and active power control systems operating in normal and post-emergency modes, and by controlling the consumption with automatic frequency unload (AFU), which operates only in emergency situations.

But the use of technological methods to eliminate power shortages is a tough decision for consumers. This paper focuses on eliminating power shortages through cost-effective methods that can help address active power shortages more leniently to the consumer.

Relationship of work with scientific programs, plans, themes. The research performed in the work correspond to the direction "Energy and Energy Efficiency", "Auction for distribution of support quota", which refers to the amendment to the Law of Ukraine № 2019-VIII of 09.12.2021 "On the Electricity market", Code distribution system, orientation of research topics (R&D) of the Department of Power Supply of the National Technical University of Ukraine " Igor Sikorsky Kyiv Polytechnic Institute".

Purpose and tasks of the research. Improving the reliability of electricity supply, decrease the shortage of active capacity of the UES of Ukraine by attracting consumers to

balancing. Development of approaches to the formation of interruption tariffs to improve the reliability of the UES of Ukraine

Object of research. Operating modes and features of electrical networks

Subject of research. Methods and means of organizing market influence on electricity consumers to increase the efficiency of the UES of Ukraine.

Practical value of the results. Modeling of the situation using price indicators was carried out, and methodological approaches were developed to establish certain tariffs for interruption of power supply.

The information base of the study consisted of laws and regulations of public administration in the field of energy, laws of Ukraine, official statistics, as well as scientific works of domestic and foreign scientists. The dissertation used software such as MS Excel, AutoCad.

Scientific novelty of the obtained results. Further development of the methodology for the formation of power interruption fees for economic stimulation of consumers to participate in reducing the capacity deficit of the UES of Ukraine, which differs from traditional approaches and is based on the principles of functioning of the modern electricity market, has acquired further development.

Approbation

1. Joint report with Bikeiev D.O., Kopchykov O.M., Gilevich K.M., Yudin S. Yu. At the conference with international participation, 2019, 2019, «Warsaw Power Engineering Students' Conference»;
2. Joint report with Bikeiev D.O., Kopchykov O.M., Gilevich K.M., Yudin S. Yu. At the conference with international participation, 2019, «Advantages and disadvantages of implementing sources of dispersed generation in the energy systems of Poland and Ukraine».

Publications

Derevianko D.G., Gilevich K.M., Dudko K.D. "Lightning protection of ground SES" / Collection of scientific works, 2020. - (Kyiv, November 26-27, 2020) -P.49-55.

Key words: ELECTRICITY, DEMAND MANAGEMENT, ELECTRICITY MARKET, POWER SHORTAGE

РЕФЕРАТ

Структура та обсяг роботи. Магістерська робота на тему «Підвищення надійності енергосистеми шляхом використання ринкових механізмів впливу на споживачів» складається зі вступу, 4 розділів, висновків та списку використаної літератури. Загальний обсяг роботи 113 сторінок, з них 16 рисунків, 13 таблиць та 31 бібліографічна довідка, 3 додатки на 12 сторінках.

Актуальність дослідження. ОЕС України не може самостійно вирішувати питання управління, тому залучення споживача до вирішення цієї проблеми є однією з таких важливих функцій. Завдання підтримання високого рівня надійності або ліквідації дефіциту електроенергії в енергосистемі є актуальним для ОЕС України протягом багатьох років. На сьогодні надійна робота ОЕС України неможлива без використання сучасних засобів регулювання частоти та активної потужності. Таке регулювання може здійснюватися як шляхом управління генерацією за допомогою систем автоматичного регулювання частоти та активної потужності, що працюють у нормальному та післяаварійному режимах, так і шляхом контролю споживання з автоматичним частотним розвантаженням (АЧР), що діє лише в аварійних ситуаціях.

Але використання технологічних методів для усунення дефіциту електроенергії є жорстким рішенням для споживачів. Ця робота зосереджується на зменшенні дефіциту електроенергії за допомогою економічно ефективних методів, які можуть допомогти врегулювати дефіцит активної електроенергії більш м’яко для споживача.

Зв'язок роботи з науковими програмами, планами, темами. Проведені в роботі дослідження відповідають напряму «Енергетика та енергоефективність», «Аукціон з розподілу квоти підтримки», що посилається на внесення змін до Закону України № 2019-VIII від 09.12.2021 «Про ринок електричної енергії». , Кодекс системи передачі, орієнтація тем наукових досліджень (НДР) кафедри електропостачання Національного технічного університету України «Київський політехнічний інститут імені Ігоря Сікорського».

Мета та завдання дослідження. Підвищення надійності електропостачання, зменшення дефіциту активної потужності ОЕС України шляхом залучення споживачів до балансування. Розробка підходів до формування тарифів на перерви для підвищення надійності роботи ОЕС України.

Об'єкт дослідження. Режими роботи та особливості електричних мереж.

Предмет дослідження. Методи та засоби організації ринкового впливу на споживачів електричної енергії для підвищення ефективності діяльності ОЕС України.

Практична цінність результатів. Проведено моделювання ситуації з використанням цінових індикаторів, розроблено методичні підходи до встановлення певних тарифів на переривання електропостачання.

Інформаційну базу дослідження склали законодавчі та нормативні акти державного управління у сфері енергетики, закони України, офіційна статистика, а також наукові праці вітчизняних та зарубіжних вчених. У дисертації використано програмне забезпечення MS Excel, AutoCad.

Наукова новизна отриманих результатів. Набуло подальшого розвитку методики формування плати за переривання електропостачання для економічного стимулювання споживачів до участі у зменшенні дефіциту потужності ОЕС України, що відрізняється від традиційних підходів та базується на принципах функціонування сучасного ринку електроенергії.

Апробація

1. Спільна доповідь з Бікєєвим Д.О., Копчиковим О.М., Гілевичем К.М., Юдіним С.Ю. На конференції з міжнародною участю, 2019, 2019, «Warsaw Energy Engineering Students’ Conference»;

2. Спільна доповідь з Бікєєвим Д.О., Копчиковим О.М., Гілевичем К.М., Юдіним С.Ю. На конференції з міжнародною участю, 2019, «Переваги та недоліки впровадження джерел дисперсної генерації в енергетичних системах Польщі та України».

Публікації

Дерев’янко Д.Г., Гілевич К.М., Дудко К.Д. “Блискозахист наземних СЕС” / Збірник наукових праць, 2020. - (Київ, 26-27 листопада 2020 р.) -С.49-55.

Ключові слова: ЕЛЕКТРИЧНА ЕНЕРГІЯ, УПРАВЛІННЯ СПИТОМ, РИНОК ЕЛЕКТРИЧНОЇ ЕНЕРГІЇ, ДЕФІЦИТ ЕЛЕКТРИЧНОЇ ЕНЕРГІЇ

LIST OF ABBREVIATIONS

PSS – power supply system.

RES – renewable energy sources.

HPP – hydro power plant.

NPP – nuclear power plant.

TPP – thermal power plant.

CHP – combined heat and power station.

SCADA – supervisory control and data acquisition.

WPP – wind power plant

OPEX – OPerating EXpenditure.

AFU - automatically frequency unload

UES – united energy system

EA - emergency automation

RP - relay protection

OPL – overhead power line

CDS - code distribution system

PAFU- protective automatically frequency unload

DR – digital relays

MPR - microprocessor relay

APCS - automated process control system

ESS - Emergency shutdown schedule

SESS – special emergency shutdown schedule

EPSLS - electric power consumption limitation schedule

SALD - special automatic load disconnection

DSO - distribution system operator

TSO - transmission system operator

SAIDI - System Average Interruption Duration Index

CONTENTS

INTRODUCTION

The United Energy System of Ukraine (UES of Ukraine) is a set of nuclear, thermal, hydraulic and storage power plants, thermal power plants, as well as power plants from renewable energy sources (wind, solar and others), main electricity networks Ukrenergo and distribution networks which are united by a common regime of production, transmission and distribution of electricity and heat.

UES of Ukraine is the basis of the country's electricity industry, which provides centralized electricity supply to domestic consumers, interacts with the energy systems of neighboring countries, provides export and import of electricity. It combines power generating capacities, distribution networks of the regions of Ukraine, interconnected by system-forming power transmission lines with a voltage of 220-750 kV.

The mode of operation of the UES is determined based on the balance of production and consumption of power, repairs of power grids and generating equipment, as well as the possibility of emergency response in case of disconnection of generating equipment at power plants and main transmission lines.

All energy systems in the world have their problems, including ensuring the reliability and quality of electricity supply, power balancing, development of RES and further implementation of new SES, WPP, etc., but such innovations have their own schedule, volatile but predictable.

Such problems in general have almost been solved with the help of technical means and the implementation of the Law of Ukraine "On the Electricity Market" on April 13, 2017.

One of the most important problems that arises with the development of the power system is to ensure the reliability of electricity supply. Thus, one of the options for solving the problem of frequency drop caused by the lack of active power in the network are technical means, in particular AFU. But when it works, it can turn off several ordinary consumers of electricity, and the whole area in difficult situations.

This paper will consider and analyze the possibility of using the new electricity market as insurance for technical equipment, for those situations where the operation of the AFU is not fully justified due to the small number of active power shortages and small areas.

Relationship of work with scientific programs, plans, themes. The researches performed in the work correspond to the direction "Energy and Energy Efficiency", “Auction for distribution of support quota”, which refers to the amendment to the Law of Ukraine № 2019-VIII of 09.12.2021 “On the Electricity market”, Code distribution system, orientation of research topics (R&D) of the Department of Power Supply of the National Technical University of Ukraine " Igor Sikorsky Kyiv Polytechnic Institute".

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SECTION 1

FEATURES OF THE ELECTRICAL NETWORK AND PROBLEMS THAT ARISE DURING ITS OPERATION

1.1 Analysis of the UES of Ukraine for 2021-2022

The UES of Ukraine today is one of the largest energy associations in Europe. The UES of Ukraine has 965 licensees for the production of electricity, of which 7 powerful power generating companies provide about 90% of all production, 7 regional electricity systems and 33 distribution system operators and 206 licensees for the supply of electricity.

The total installed capacity of electricity stations of the UES of Ukraine as of 01.01.2022 [1] (excluding energy generating facilities of the Crimean electricity system and the temporarily uncontrolled territory of Donetsk and Luhansk regions) is 54,233 GW, of which 51.46% are thermal power plants (in particular, thermal power plants, CHPPs, power plants), 25.51% - nuclear power plants, 11.61% - hydroelectric power plants and sonar power plants, 11.42% - at power plants, which work on alternative energy sources — wind farm, SPP, BioES

The main generating capacities of the UES of Ukraine (as of 01.01.2022) are focused on [1]:

- NPP - 13,835 MW (four nuclear power plants (15 power units, of which 13 with a capacity of 1,000 MW and 2 with a capacity of 415 and 420 MW));
- TPP GK – 21842 MW (12 thermal power plants with units with a single capacity of 150, 200, 300 and 800 MW (75 power units, including capacity: 150 MW - 6, 200 MW - 31, 300 MW - 32, 800 MW - 6 units) and 3 turbogenerators,);
- HPP – 4830 MW (cascades of 7 hydroelectric power plants on the Dnieper and Dniester rivers with a total number of hydraulic units 103 units);
- GAES – 1488 MW (11 hydraulic units with capacity from 33 to 324 MW);

- CHP – 6104 MW (3 large CHPs with power units 100 (120) MW — 4 units, and 250 (300) MW — 5 units);
- SPP – 6414 MW;
- WEIGHT – 1529 MW;
- Biofuel plants 256 MW;

The development of RES did not go around and Ukraine, so with the growth of the number of solar power plants, wind farms, and other sources of RES, the balancing problem becomes in the power system, which is already difficult to balance, due to the uneven load schedule, and the structure of the power system has its own characteristics of electricity production, which in the complex makes the balancing process still more complicated. Now, the consumer does not use electricity quite predictably, and the generation of electricity must be carried out according to the planned scenarios of legislation, which in the complex requires strict balancing solutions, one of which was EA - AFU devices.

Centralized dispatching (operational and technological) management, maintaining balance in the IPS of Ukraine and organizing parallel work with energy systems of other states is performed by the state enterprise "National Energy Company "Ukrenergo", which performs the functions of the transmission system operator. Currently, the UES of Ukraine has been synchronized with the European Network of Transmission System Operators for Electricity (ENTSO-E) since March 16, 2022. Electrical connections of the UES of Ukraine are carried out on networks of 110-750 kV. System-forming networks with a voltage of 220 - 750 kV include main and interstate electrical networks (power transmission system). They ensure the issuance of electricity from powerful power plant units and its subsequent transfer to the distribution networks of the regions of Ukraine (electricity distribution system), as well as the export and import of electricity with the power systems of neighboring countries. Power transformation is ensured with the help of autotransformers and transformers with a voltage of 750/330 kV, 330/220 kV, 400/330 kV, 330/110(150) kV, 220/110(150) kV, 150/110 kV.

According to the report of the NEURC for 2019[2], 103 substations (PS) with a voltage of 110 – 750 kV with a transformer capacity of 78,553.1 are on the balance sheet of NPC Ukrenergo. MVA. Of these, the substation 220 kV – 33 pcs. with a capacity of 4,424 thousand tons. MBA, 330 kV – 88 pcs. with a capacity of 41,502 thousand tons. MBA, 400 – 2 pcs., 500 kV – 2 pcs., 750 kV – 8 pcs. with a capacity of 16,738 thousand tons. MVA and 110 kV – 4 pcs. (port nodes of solar power plants) [1].

Costs in the networks of the transmission system operator are 3.773 million kWh, which is 2.58% of the release to the network.

The electricity distribution system has 752,923 thousand tons. km of air and 73,787 thousand km. km of cable power lines with a voltage of 0.4 – 150 kV, as well as 204,610 thousand km. transformer substations with a voltage of 6 – 150 kV. As of 2018, there are 33 electrical distribution enterprises in Ukraine. The UES of Ukraine unites seven regional electricity systems: Dnipro, Western, Crimean (now located on the territory of the Autonomous Republic of Crimea, which is not controlled by Ukraine), Southern, Southwestern, Northern and Central.

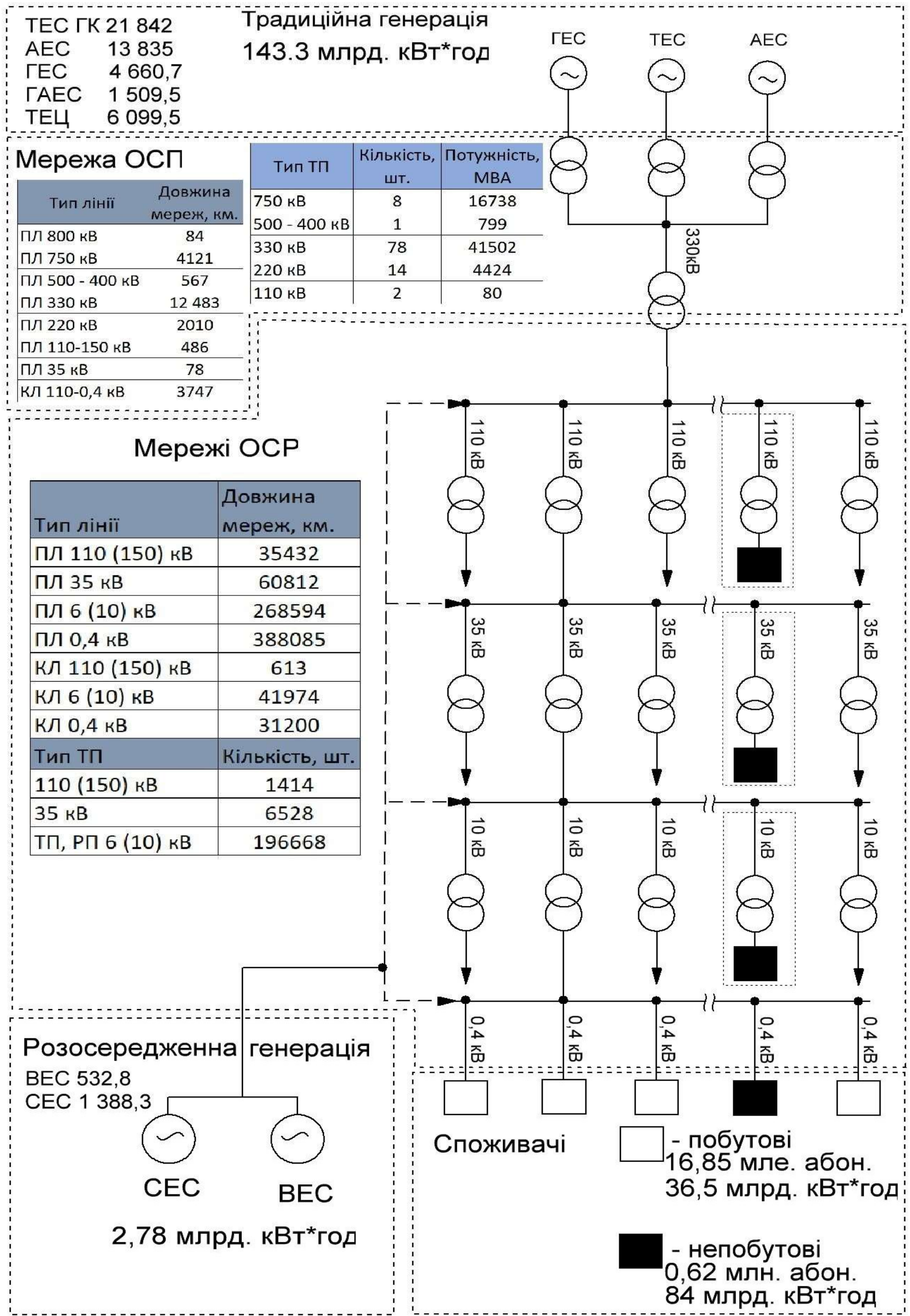


Figure 1.1 − Structure of electrical networks in the UES of Ukraine [2]

Due to the long operational period and lack of funding for the modernization of electrical equipment, power lines are in a worn state, in the same condition there are protection equipment and automation and transformer substations.

Electricity transmission system: The length and life of the overhead transmission by voltage class (as of 31.12.2019) is given in Table 1.1

Table 1.1 Length and lifetime of the overhead power line voltage class (as of 31.12.2019) [3]

Voltage class	Total, km		Incl. are in operation (years)			
	On the track	By chain	Up to 25	From 25 to 30	From 30 to 40	40 and more
800 кВ	98,54	98,54	-	-	-	98,54
750 кВ	4403,171	4403,171	692,65	0	2045	1664,571
500 кВ	374,76	374,76	38,1	-	159,6	177,06
400 кВ	338,95	338,95	-	-	-	338,95
330 кВ	12970,839	13533,652	1112,645	467,058	2063,988	9889,961
220 кВ	3019,385	3975,965	178,628	0	265,517	3531,82
110 кВ	458,288	568,9	66,43	5,42	61,005	436,045
35 кВ	112,441	114,051	18,858	2,46	12,53	80,203
Total:	21776,374	23407,989	2107,331	474,938	4608,59	16217,15

Table 1. 2– Characteristics of electric power systems, length overhead power line as of 01.01.19. [3]

Name of power system	They are in operation (years), km.				Total length, km.
	Up to 25	25-30	30-40	More than 40	
Dnieper	394,998	274,158	1079,759	3207,982	4956,897
Donbass	114,456	-	309,836	1432,307	1856,599
Western	205,85	89,46	755,2	2745,85	3796,36
Crimean	150,626	-	141,88	1018,609	1311,115
South	593,3	54,1	826,776	1176,796	2650,972
Southwestern	229,54	-	548,35	1485,51	2263,4
North	150,181	-	972,919	2729,636	3852,736
Central	483,35	20,5	388,88	1808,06	2700,79
Total	2322,301	438,218	5023,6	15604,75	23388,869

The number of substations by voltage class and the installed power of autotransformers and power transformers (as of 31.12.2019) are shown in Table 1. 3

Table 1. 3 Number of substations by voltage class and installed power of autotransformers and power transformers (as of 31.12.2019) [3]

Voltage class, kV	Number of substations, pcs.	Installed power AT та PT, MVA
110	6	376
220	33	9207,2
330	88	49597,9**
400	2	2008
500	2	1753
750	9	18736
Total	140*	81678,1

*17 substations are located on the territory of the temporarily occupied Autonomous Republic of Crimea and 17 substations are located on the territory temporarily uncontrolled by the Government of Ukraine.

** the total capacity takes into account autotransformers at the 330 kV Mirgorod substation with a capacity of 200 MW and 330kV Rudna substation with a capacity of 250 MW, which are installed at the expense of the Southern Railway but are not accepted on the balance sheet of NPC Ukrenergo.

According to the statistics given in Table 1.1, lines operated for less than 25 years have a length of 2,322,301 km. which is 7.76%, the lines operated in the period from 25 to 30 years have a length of 438,218 km. which is 5.68%, the lines operated in the period from 30 to 40 years have a length of 5,023,600 km. which is 22.33%, 15,506,21 km have a service life of more than 40 years and make up 64.23% of the total length of the lines. Such statistics indicate that more than 86% of lines with a voltage of 35 - 800 kV exceed the period of established operation and are considered obsolete, which is the cause of emergencies and losses in the network. Most power lines were built before 1975 and 1990. With electric substations, the situation is somewhat better, since about 45% of transformer substations were built in the period from 1991 to 2016, the operational period of which did not exceed 30 years.

Table 1.4. – General characteristics of RP and EA devices for years of operation [1]

Name of power system	Number of devices in operation				Total devices
	до 25	25-30	30-40	40+	
Dnieper	3442,5	2559	5043	5152	16196,5
Donbass	3417	3085	2973	4132	13607
North	4241	1212	1220	951	7624
Central	3202	2636	4011	1025	10874
Southwestern	3349	548	961	1027	5885
South	5088	870	2900	830	9688
Western	22740	10444	17108	131117	181409
Total	45479,5	21354	34216	144234	245283,5

The situation with RP and EA devices is also no better than 50% of the equipment operated for more than 50 years, which adversely affects the performance of equipment and leads to an increase in emergency situations and an increase in SAIDI and SAIFI indicators.

1.2 Analysis of existing problematic issues regarding ensuring the reliability of power supply

For the UES of Ukraine, there have always been urgent problems: changing the frequency of the electrical network, falling voltage in the network and others.

Given the fact that the UES of Ukraine is developing, new sources of RES are emerging, old substations are being reconstructed and new, emergency situations are being built during the implementation of these processes, as well as due to weather conditions are inevitable. Emergency situations such as: KZ, falling voltage in the network, reducing the frequency of the network, a shortage or surplus of active power in the network, can cause major problems both at a high level of the power system and at lower levels, such as the end user.

So, one of the prerequisites for my study was the indicators of non-supply of electricity shown in Figure 1.4, SAIDI are shown in Figures 1.2, 1.3, which in Ukraine are quite large compared to European countries.

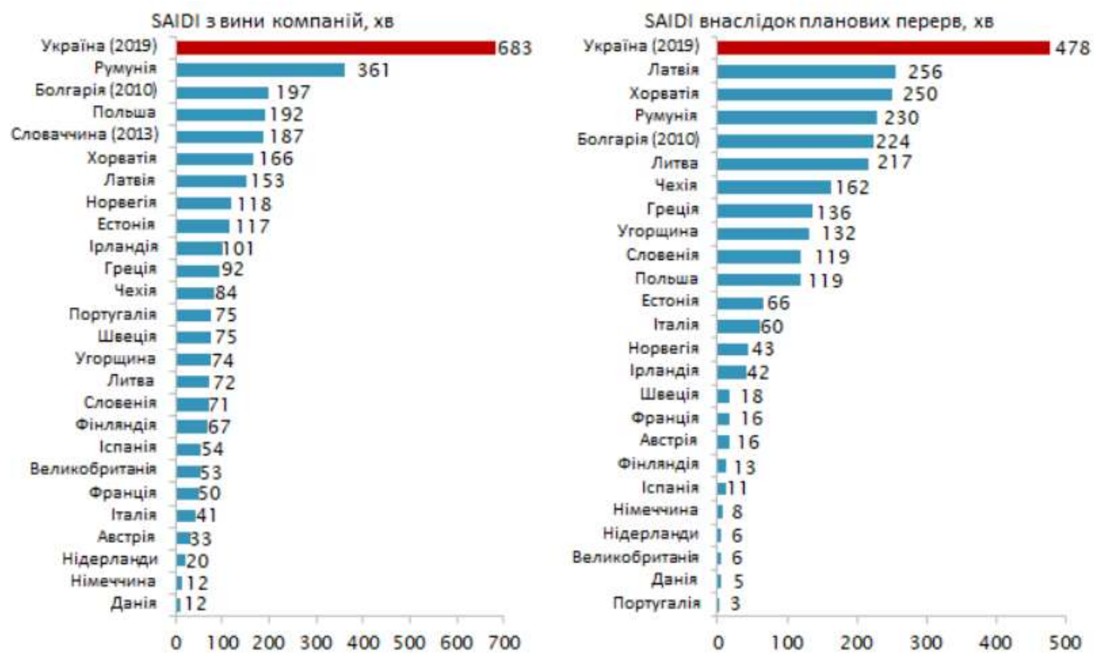


Figure 1.2 SAIDI indicators of Europe (2016) and Ukraine (2019) [2]

Figure 1. 3. Dynamics of SAIDI and ENS indicators for 2012 – 2019 (fault of companies) [2]

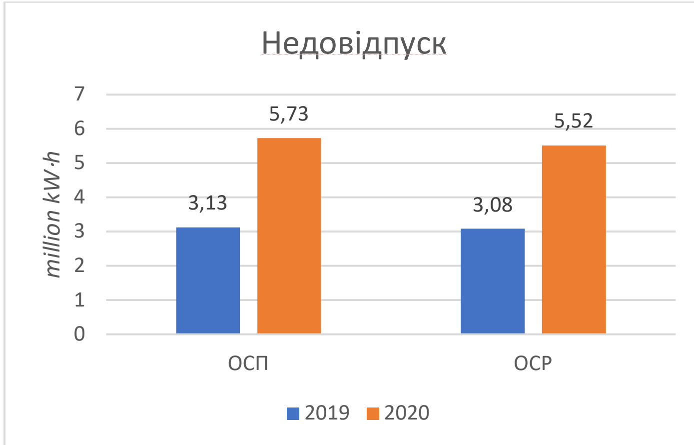


Figure 1.4 Comparison of electricity outages for 2019–2020[2]

Also, after Ukraine's accession to the European energy system ENTSO-E on March 16, 2022, these indicators become even more important.

Table 1.5 shows compression of the number of failures of power plants for 2019-2020, which shows that the number of failures increased in 2020 compared to 2019 due to the fault and without fault of staff.

Table 1.5 Compression of the number of failures of power plants for 2019-2020 [4]

Comparison of the number of failures of power plants for 2019-2020			
Object Name	**Refusals for 2019 (The fault of the staff/without the fault of the staff)**	**Refusals for 2020 (The fault of the staff/without the fault of the staff)**	**Growth (The fault of the staff/without the fault of the staff)**
Dniproenergo	**52/8**	**61/18**	**9/10**
Donbassenergo	**14/2**	**18/5**	**4/3**
Zakhidenergo	**55/22**	**67/27**	**12/5**
Centrenergo	**34/5**	**37/7**	**3/2**
Skhidenergo	**25/23**	**36/32**	**11/9**
Myronivska TPP	**0/2**	**0/3**	**0/1**
"Kyivteploenergo"	**0/3**	**2/5**	**2/2**
"Ukrhydroenergo"	**2/5**	**2/7**	**0/2**
NPC "Ukrenergo"	**63/9**	**91/10**	**28/1**
NNEGC "Energoatom"	**0/5**	**2/9**	**2/4**
Separate CHP's	**26/12**	**58/12**	**32/0**

Read more about power failures for 2020 compared to 2019 in annex A.

Today, reliable operation of the united power system (UES) of Ukraine is not possible without the use of modern means of frequency control and active power. Such regulation can be carried out both by controlling generation using automatic frequency and active power control systems, which operates in normal and post-accident modes, and by controlling the volume of consumption of automation frequency unloading (AFU), which works only in emergency situations. One of the main problems of operation of power systems is to ensure its reliable and stable operation in emergency modes. According to the analysis of world experience [5], the occurrence of the most severe accidents is usually associated with the loss of significant volumes of generating capacity or the loss of the district's connections with a significant amount of load. Given the extreme importance of the work of AFU during the elimination of emergency regimes, accompanied by a decrease in frequency, the analysis of approaches to the formation of AFU queues in the UES of Ukraine is of particular relevance. To conduct a comprehensive analysis of the problem of AFU organization in the UES of Ukraine, a promising approach is considered in the work, which considers the absolute value of the frequency and frequency reduction rate, the method using the algorithm for optimal configuration of the AFU system, taking into account the structure of generation and consumption, as well as a modern approach to the formation of AFU.

1.2.1 General principles of AFU functioning

AFU devices are classified into categories [6]:

- PAFU is installed to prevent the occurrence of an accident at a nuclear power plant. Such devices are triggered when the frequency reaches 49.2 Hz. The trigger time is 0.5 s.
- AFU-1 is triggered in case of a sharp drop in frequency to 48 Hz. AFU-1 refers to fast-acting systems with a speed of 03-05 s.

- AFU-2 starts work with a prolonged slow drop in frequency. It operates at the same frequencies as AFU-1, but the shutter speed is set much longer (5-10 or 70-90 seconds).

Raising the frequency is implemented with the help of FAR, which is the re-inclusion of consumers in automatic mode after the functionality of the power system is fully restored.

In accordance with [6] the general requirements for automatic frequency unloading are:

- AFU is designed to prevent dangerous frequency reduction in the event of a shortage of active power in the UES of Ukraine or its separate part by turning off part of the load of consumers:

1. small queues (volumes) with a relatively slow decrease (slide) of the frequency (not more than 1.7 Hz/s;) to stop its decline. Slow frequency reduction is most characteristic of parallel operation of the UES of Ukraine with adjacent power systems or in case of minor emergency power shortages.
2. in case of rapid decrease in frequency (more than 1.7 Hz/s;) queues (volumes) in accordance with the emergency power shortage that has arisen (frequency reduction rate). As a rule, a significant rate of frequency reduction is more characteristic of the autonomous operation of the UES of Ukraine or its separate part in the event of an emergency power shortage.
3. small queues (volumes) to increase the frequency after the end of the process of its reduction.

- AFU has a decentralized structure and is performed in the form of a set of separate autonomous devices that act to disable specified connections at power plants, as well as on electric power plants, electricity companies and consumers. AFU devices, as a rule, must be located at the facilities of electricity systems or energy transfer companies.

When determining the volume of load, which should be turned off by the action of AFU, it is necessary to consider the most severe emergency modes in normal and repair schemes and other possible options for the occurrence of a significant emergency deficit of active power, starting with local accidents and ending with system-wide accidents in the UES of Ukraine, taking into account the fact that the same AFU devices should prevent dangerous frequency reduction as during local, and during system accidents.

The choice of the possible value of the emergency power shortage should be performed for all the most characteristic and difficult, taking into account the balance and repair schemes, modes of operation of the power system: evening and morning highs, night and day minimums, for working, weekends and holidays in different periods of the year, including the watershed period.

When determining the amount of load that is turned off by the action of AFU, as a rule, it is necessary to proceed from the possibility of:

- shutdown of all nutrient lines of the consumer or scarce area;
- turning off the power of the largest unit or two units of the power plant if they work on the tires of the power plant through a common switch;
- the occurrence of asynchronous gait along a separate intersection and, as a result, the development of an accident with the shutdown of part of the generated power;
- turning off the power of individual units and power plants in the scarce part of the UES of Ukraine, followed by the shutdown of "weak" bonds in individual intersections due to an increase in the power transmitted through the intersection, above the limit of its stability;
- complete separation of the UES of Ukraine from adjacent power systems or its division into parts with the shutdown of intersystem (main) connections in case of violation of their stability due to the occurrence of significant emergency deficits of active power (for example, in the case of de-energization (landing on "0") of the largest power plant or unloading of NPP power units in accordance with the technological regulations while reducing the frequency below 49.0 Hz);

Automatic frequency unloading (AFU) is used to preserve the functionality of the power system and consumers of the 1st category of supply in situations of a sharp decrease in the amount of active power in the power grid. AFU refers to emergency automation, which is aimed at improving the reliability of electrical systems. The principle of operation of this method is based on the disconnection of a less important part of electricity consumers from the grid.

Reducing the frequency can have a very negative impact on the performance of the energy system and can cause a man-made or environmental disaster. For example, even a slight drop in frequency by 2-3 hertz causes a decrease in the supply of water to the capacitor of the power plant by 25-40%, can disable pumps that supply water to boilers.

In accordance with the provisions of paragraph 11.4.6 of Chapter 11.4 of Section XI of the Code of Distribution Systems, approved by the Resolution of the NEURC of 14.03.2018 No. 310 [7] (hereinafter referred to as the CDS), the parameters of electricity quality at the points of connection of consumers in normal operating conditions must comply with the parameters defined in DSTU EN 50160:2014 "Characteristics of power supply voltage in general purpose electrical networks" (hereinafter referred to as DSTU EN 50160:2014).

The main indicators of the quality of electricity are defined in paragraphs 11.4.7 – 11.4.12 of Chapter 11.4 of Section XI of the CDS.

The standard rated voltage of the U_n for general-purpose low voltage networks is set to 220 V between the phase and zero wires or between phase wires:

- for three-phase four-wire networks: U_n = 220 V between phase and zero wire;
- for three-phase three-wire networks: U_n = 220 V between phase wires.

The voltage change should not exceed ± 10% of the nominal voltage. The frequency of power supply voltage for low voltage networks should be within:

1) for systems that are synchronously connected to the UES of Ukraine - 50 Hz ± 1% for 99.5% of the time per year and 50 Hz + 4% (- 6%) within 100% of the time;

2) for systems without synchronous connection to the UES of Ukraine - 50 Hz ± 2% for 99.5% of the time per year and 50 Hz ± 15% within 100% of the time.

Also, a further increase in the shortage of active power in the power grid, accompanied by an increasing avalanche-like nature by the process of frequency drop. This process is called an avalanche of frequency. In addition to the above negative consequences of reducing the frequency, it is necessary to mention another one - a drop in voltage. This factor has an additional negative impact on consumers. To avoid the consequences of the shortage of active power, it is necessary to disconnect part of consumers in the network. Thus, the state and availability of the AFU system at substations is very important.

But such a solution to the problem can adversely affect the end user, since in the case of the operation of AFU, a power outage is possible not only locally, but also in a large area, depending on the scale of the accident. So, despite the category of reliability of the power consumer for the II and I categories, even with two independent power supplies, both can turn off, which can adversely affect the infrastructure and the power consumers themselves.

1.2.2 The method of forming AFU, which is used in the UES of Ukraine

According to p. 6.1.1. [6], AFU is designed to prevent a dangerous decrease in frequency in the event of a shortage of active power in the UES of Ukraine or its separate part by turning off part of the load of consumers. Turning off consumers should be carried out in small queues with a slow decrease in frequency. Today, the critically accepted rate of frequency reduction is more than 1.7 Hz / s, but recommendations for determining the critical rate of frequency reduction should be determined by a special technique based on large-scale calculation experiments on a high-quality mathematical model of the power system. Work on the formation of a methodology for determining the critical rate of frequency reduction, as well as the setting and selection of settings of AFU devices that respond to the rate of frequency reduction, is planned by the scientific and technical center of the electric power industry. In accordance with the "Instructions on the preparation and application of schedules for the restriction and emergency shutdown of consumers, as well as emergency systems for reducing electricity consumption" [6], AFU is developed, used and reviewed in accordance with the "Rules for the use of systemic emergency automation to prevent and eliminate dangerous reduction or increase in frequency in power systems" [6]. In Tables 1. 6, 1. 7 shows the current structure of AFU as a percentage and in the loads of the past year.

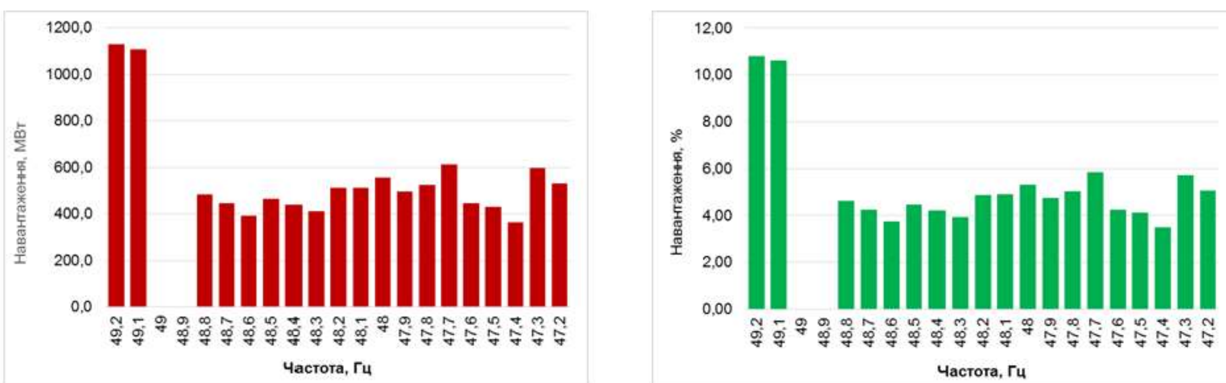
Table 1.6 Load distribution in the UES of Ukraine, which is turned off by the action of AFU-1, depending on the insertion by frequency

№	Frequency of operation	Switching load capacity, MW	Proportion of switching load power,%
1.	49,2	1130,4	10,81
2.	49,1	1108,2	10,60
3.	48,6	482,8	4,62
4.	48,5	445,5	4,26
5.	48,4	391,4	3,74
6.	48,3	465,9	4,46
7.	48,2	440,1	4,21
8.	48,1	411,8	3,94
9.	48	510,8	4,89
10.	47,9	512,8	4,91
11.	47,8	554,6	5,31
12.	47,7	496,0	4,74
13.	47,6	524,5	5,02
14.	47,5	611,2	5,85
15.	47,4	445,1	4,26
16.	47,3	431,1	4,12
17.	47,2	365,2	3,49
	Total:	10453,6	100

Table 1.7 Load distribution in UES of Ukraine, which is switched off by AFU-2 (combined), depending on the setpoint by frequency

№ п/п	Frequency of operation	Switching load capacity, MW	Proportion of switching load power,%
1.	49	1643,4	21,1
2.	48,9	1696,0	21,8
3.	48,8	2426,5	31,2
4.	48,7	2012,4	25,9
Total:		7778,3	100

A graphical display of the loads that are turned off by the action of AFU-1 in the UES of Ukraine is shown in Fig.1.5



а) б)

Pic. 1.5 Graphical display of load capacity in the UES of Ukraine, turned off by the action of AFU-1: a) in absolute units; b) as a percentage.

Thus, considering the data given in tables 1.6, 1.7, it can be concluded that disabling so much power for consumers can have serious consequences for production. Although the frequency control procedure is very important for the power system, consumers are only interested in their interests, which goes against the interests of the power system. Thus, softer power balancing solutions are needed that will satisfy the interests of both parties. One of these solutions is the "New Electricity Market", introduced in 2017.

1.3 Analysis of alternative technical solutions

One of the alternative solutions was covered in the article [**8**]. In it, the authors proposed the concept of creating and functioning of a centralized and multichannel control system for medium voltage switchgears, the main feature of which is the implementation of algorithms for protecting the primary and backup connection of switchgears in the computing node of the substation in dual mode or a backup server. (Front-End-Controller, FEC).

The proposed system provides enterprises and power grids with a relay protection and automation system, which is cost-effective and more practical than traditional, with various electroautomatics systems for power facilities of the most common medium voltage distribution networks, as well as with power supply systems of industrial enterprises.

In addition, this approach will improve and simplify the implementation of modern adaptive relay protection and automation algorithms in power supply systems and electrical networks; this will provide the most efficient and appropriate technological elements for such systems and networks that comply with IEC 61850. The article analyzes the issues of reliability and quality of work of the main part of the developed control system - centralized relay protection system and automation, which ensures the compliance of all functions of medium voltage electrical objects, including the function of relay protection of the main connections. The main elements of this system are considered, and the performance of the central computing central controller (s) is evaluated. It is determined that the requirements for the performance of the controller(s) for the medium voltage distribution substation do not exceed the requirements for existing SCADA controllers supplied by leading manufacturers in the electricity automation market.

In my opinion, this option of solving some problems of the power system is advisable for implementation in the UES of Ukraine, but first you need to solve many existing problems so that in the future there is a stable base for the transition to new equipment.

Another technical option for solving the power balance problem is the installation of accumulating devices. But this option is currently very difficult to implement. For example, experts of EDF (France) argue that the situation can be improved with the help of energy storage devices. However, despite significant progress, the capabilities of accumulating devices remain uncertain. The French estimate that to accumulate 1 TWh of electricity requires a battery weighing a million tons, including 120 thousand tons of lithium. This is much more than its annual production in the world. Whether lithium reserves will last long is a question that has not yet been answered. There are doubts about the ability of batteries to store stored electricity for a long time.[9]

Also, one of the options for the existing problem is the local installation of accumulating devices for the I and I special power supply group, to replace outdated and non-ecological diesel generators. infrastructure for the disposal of lithium elements. And in the case of the use of lead-acid batteries significantly increases the weight and size of batteries compared to lithium.

However, on June 7, 2022, President of Ukraine signed draft law No. 0150 dated May 11, 2022, on ratification of guarantee agreements between Ukraine and the International Bank for Reconstruction and Development (IBRD) within the framework of the investment project on the installation of hybrid energy storage systems in PJSC Ukrhydroenergo. The funds will be directed, in particular, to the installation of 197 lithium-ion energy storage systems (SNE) on the territories of Ukrhydroenergo facilities, which are planned to be attracted to provide auxiliary services for frequency and power control. In addition, for its own needs of hydroelectric power plants and hydroelectric power plants and SNE charging, it is planned to install 63.9 MW of solar photovoltaic stations. As for Ukraine, this is the beginning of the use of accumulating elements for balancing, which in the future will become the basis for further development.

So we can conclude that if for the energy sector of France, which is many times larger than Ukraine in terms of installed capacity and financial capabilities, such large volumes of lithium for batteries are needed, then even for certain options where the use of batteries will be required and justified, today it is impossible to use them, due to the prohibitively high price and imperfection of this technology in terms of electricity density.

1.4 Possible ways of development of technical equipment that ensures frequency stability in the power system

Currently, most of the RP and EA devices used in Ukraine, in particular AFU based on frequency relays, electricity grid belongs to the generation of electromechanical and microelectronic relays and do not meet modern scientific and technical requirements [10]. One of the areas of improvement is the use of microprocessors to perform the functions of relay protection and automation. Digital devices have a few advantages over systems made on a traditional element base, including broader performance and the ability to integrate them into APCS. DR systems have been used in RP and EA systems for more than ten years. Leading electrical engineering firms: SIEMENS, AREWA (ALSTOM), ABB, SCHNEIDER ELECTRIC, GE have developed a significant amount of DR protection and automation. It should be noted the high technological quality of these devices. But their widespread use in Ukraine's electricity networks is hampered by several problems. Firstly, insufficient efficiency of operation during operation in conditions of domestic electricity grids. Secondly, the impossibility of direct integration of DR of foreign production into most of the current APCS of Ukraine. Thirdly, the high price of such devices. The first two problems can be solved by developing or improving the characteristics of the functioning of existing methods for processing input information, creating algorithms for protections and automation adapted to the working conditions of domestic electricity grids, algorithms for exchanging information with existing APCS. Currently, the reduction in the cost of the DR of foreign 8 production is achieved only by reducing their functionality. Moreover, adaptation to domestic operating rules leads to an increase in the cost of the device.

Conclusions to the first section

In this section, the main ways and opportunities that are currently being implemented in AFU systems were investigated. A comprehensive analysis of the equipment's capabilities for managing electricity demand in the UES of Ukraine, namely AFU, was carried out. Classical methods of using technical means using relays to prevent changes in the frequency of the electrical network were considered. The method of forming AFU, which is used in the UES of Ukraine, was also analyzed and analyzed alternative technical options for solving the problem of the shortage of active power in the power system.

SECTION 2

THE ELECTRICITY MARKET AS AN ECONOMIC TOOL FOR SOLVING THE PROBLEM OF RELIABILITY OF THE POWER SYSTEM

2.1 Market mechanisms for ensuring the functioning of the electrical network

The UES of Ukraine is not ideal in the issue of reliability of electricity supply now, throughout the country there are electricity connection units, the capacity of which is limited. Both during Ukraine's war with the Russian Federation and in peacetime, there may be problems when one or more nodes fail or lose their full capacity, which may lead to a shortage of active power in a certain area. So, if the technical means of the EA in particular AFU do not respond to this in time, it can lead to enormous consequences. Thus, AFU plays an important role both for the entire power system and locally for a particular area.

Having considered the technical problems that were presented in the first section, there was a need to analyze these tasks through the prism of market relations. Namely, how the problem of lack of active power in the network can be solved, softer in relation to the end user, by way.

As part of the EU's third energy package in Ukraine, on July 1, 2019, the New Electricity Market began to operate. In accordance with Section XIV "Law on the Electricity Market"[11] within the framework of this reform, the electricity market was divided into several separate parts: the Market of Bilateral Contracts, the Day-Ahead Market, the Intraday Market, the Balancing Market, the Auxiliary Services Market(next ASM).

Each of these markets exists separately in order to gradually divide the purchase of electricity in time convenient for electricity consumers, transparency and ease of trading in these markets. Trading in these markets is gradual and convenient for both suppliers and consumers.

2.1.1 Market of bilateral agreements

In accordance with Article 66 of Section XIV of the "Law on the Electricity Market"[11] the purchase and sale of electricity under bilateral agreements is carried out by manufacturers, electricity suppliers, transmission system operators, distribution system operators, traders, guaranteed buyer and consumers.

The relevant bilateral treaty shall establish:

1) the subject of the contract;

2) the price of electricity determined in monetary units;

3) the volume of electricity and schedules of hourly volume of purchase and sale of electricity;

4) terms and procedure for the supply of electricity;

5) the procedure for notification of contractual volumes of purchase and sale of electricity under a bilateral agreement;

6) the procedure and form of payments;

7) terms and procedure for registration of acts of acceptance and transfer of volumes of purchase and sale of electricity;

8) rights, obligations and responsibilities of the parties;

9) The term of the contract.

The regulator has the right to establish the maximum validity period of bilateral agreements, which cannot be less than six months.

The parties to the bilateral agreement in accordance with the rules of the market inform about the contractual volumes of purchase and sale of electricity under the concluded contract. Such a notice is the basis for entering these volumes into the daily electricity schedules of the relevant market participants in accordance with market rules.

The parties to the bilateral agreement, which are part of one vertically integrated entity or are affiliated with each other, within three working days after the conclusion of the bilateral agreement, inform the Regulator about the subject of the contract, the price of electricity and / or the procedure for its calculation (formation), the amount of electricity and the schedule of hourly purchase and sale of electricity, the terms and procedure for the supply of electricity.

Therefore, such a market makes it possible to purchase such a quantity of electricity that will satisfy the basic requirements of the consumer, with long-term supply, at a price unchanged in time, about the price written in the contract.

And to solve the problem given in section 1.2, it is not economically suitable, since the contract is drawn up in advance and the amount of electricity purchased cannot be changed.

2.1.2 Day-ahead market and intraday market

According to Article 67 of Section XIV of the "Law on the Electricity Market"[11] for participation in the day-ahead market and the intraday market, market participants conclude an agreement with the market operator on participation in the day-ahead market (next DAM) and the intraday market (next IDM), the typical form of which is an integral part of the rules of the day-ahead market and the intraday market.

The market operator has no right to refuse to conclude an agreement on participation in the day-ahead market and the intraday market if the market participant has duly fulfilled all the conditions of the day-ahead market rules and the intraday market regarding access to the day-ahead market and the intraday market.

To sell/purchase electricity on the day-ahead market and the intraday market, participants of this market submit their offers (applications) to the market operator. The form and procedure for submitting proposals (applications) are determined by the rules of the day-ahead market and the intraday market.

The price of purchase and sale of electricity on the day-ahead market is determined for each settlement period by the market operator on the principle of marginal pricing based on the balance of total demand for electricity and its total supply, and in the intraday market - on the principle of pricing "at the declared (proposed) price" in accordance with the rules of the day-ahead market and the intraday market.

For the day-ahead market, the billing period is every hour following the day of trading.

The intraday market is an auction where the purchase is made after the auction on the day-ahead market has ended, but only during the day.

Prices on the day-ahead market and the intraday market are free (market) prices.

According to the results of trading, in accordance with the rules of the day-ahead market and the intraday market, the price and volumes of purchase and sale of electricity for each billing period and other indicators are published.

The marginal prices [1] are:

on DAM/IDM:

- For minimum load (from 0^{00} to 8^{00} and from 23^{00} to 24^{00}): 959,12 UAH/MWh (excluding VAT)
- Maximum load (from 8^{00} to 23^{00}): 2048.23 UAH/MWh (excluding VAT)

on BM: not less than 70% and not more than 115% of the actual prices of DAM

on ASM of 2020:

formed in accordance with the Market Rules "Marginal Prices" (subject to competition):

– loading 1128 UAH/MWh (excluding VAT);

– unloading 255 UAH/MWh (excluding VAT).

formed according to the methodology approved by the Regulator (in the absence of competition):

– loading 499 UAH/MWh (excluding VAT);

– unloading 282 UAH/MWh (excluding VAT).

It can be concluded that such markets make it possible to purchase so much electricity that will be needed in addition to the amount that has already been purchased on the market of bilateral contracts, when changing the technological process of production or for similar reasons, but the price of this electricity will vary at auction, and increase the closer the hour when electricity is needed.

And to solve the problem given in section 1.2 economically, these markets are not suitable, since trading takes place at least an hour before the required delivery hour, which is not suitable for situations of a sharp decrease in active power in the network.

2.1.3 Balancing market

In accordance with Article 6of Section XIV of the Law on the Electricity Market [11] in the balancing market (BM), the transmission system operator shall:

- purchase and sale of electricity to balance the volume of electricity supply and demand within the current day;

- purchase and sale of electricity in order to regulate the imbalances of electricity of the parties responsible for the balance sheet.

The transmission system operator to ensure operational security has the right outside the balancing market to purchase load reduction services by the manufacturer who sells electricity at a "green" tariff or at an auction price.

In the balancing market, electricity producers (generation) interact with the Transmission System Operator (NPC Ukrenergo) without the participation of electricity suppliers. Electricity suppliers operate in the market of imbalances, where they can sell surpluses and buy the volumes of electricity that are lacking. In the case of electricity purchase, the price will be much higher than the planned price of electricity, since it consists of the highest price of the balancing market and the day-ahead market, which was formed at the time of filing an application for purchase and multiplied by the coefficient regulated by the regulator (NEURC) 1.05. Suppliers will be able to sell excess electricity at a much lower price, focusing on the lowest price of BM and DAM, multiplied by a coefficient of 0.95.

Prices for loading and unloading in the balancing market for 2019 and 2020 are shown in Figure 2.1, 2.2

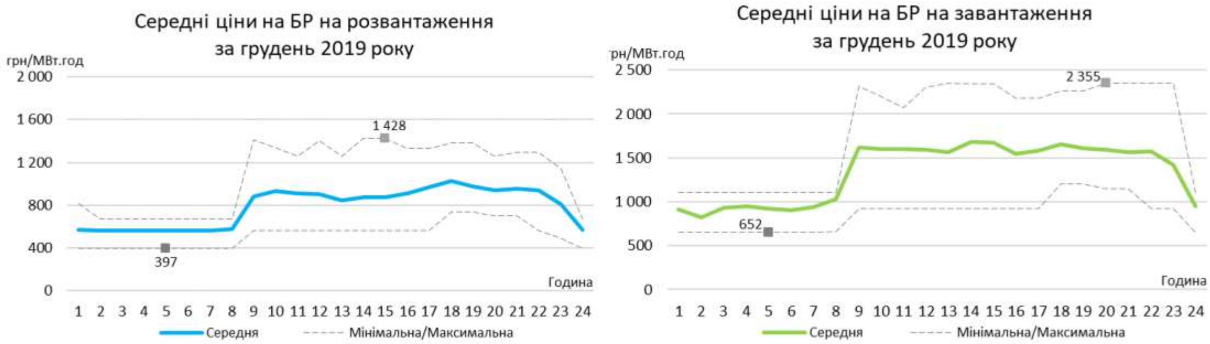


Figure 2.1 average prices for BM for unloading and loading for December and January 2019

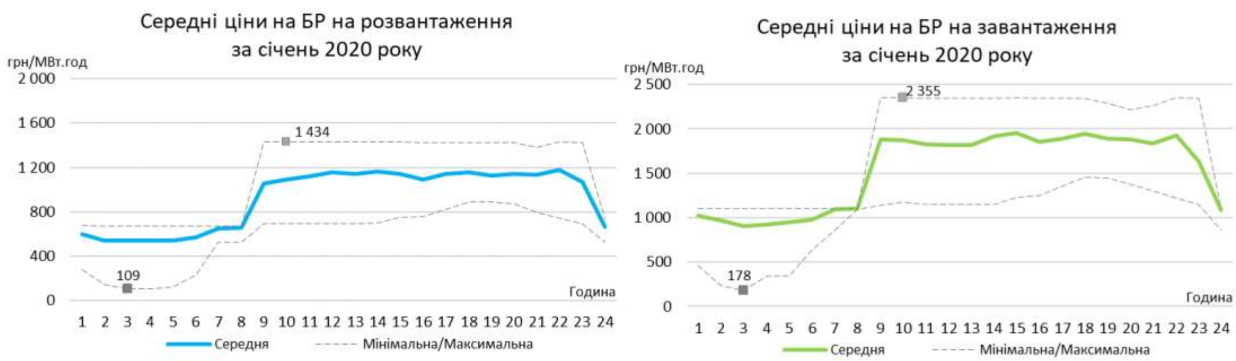


Figure 2.2 average prices for BM for unloading and loading for December and January 2020

Note:

average price for BM for unloading:

- December 2019 – 703 UAH/MWh;
- January 2020 – 845 UAH/MWh;

to download:

- December 2019 – UAH 1,477/MWh,
- January 2020 – UAH 1,682/MWh.

Based on the data on BM prices, I can conclude that the price has increased firstly due to the complications of balancing the power system due to the development of RES, and secondly, such a price can be an attractive factor for consumers who can participate in balancing, and a fine for consumers who are not involved in balancing for various reasons and become a problem for the power system. Inflation has also been affected by this price.

Balancing in the market of imbalances is carried out by the total volume of purchase / sale, and not for each consumer, which allows electricity suppliers with many consumers to compensate for each other's imbalances without much loss.

2.1.4 Ancillary Services Market

According to Article 69 of Section XIV of the "Law on the Electricity Market"[11] in the market of auxiliary services, the transmission system operator buys auxiliary services on a market and transparent basis to ensure the reliable operation of the UES of Ukraine and the proper quality of electricity.

Participants in the auxiliary services market are:

1) the transmission system operator that purchases and/or uses ancillary services;

2) ancillary service providers that offer and/or provide support services.

In the market of auxiliary services, auxiliary services may be purchased/provided to provide:

1) regulation of frequency and active power in the IPS of Ukraine, namely the provision of:

- frequency support reserves (primary regulation);
- reserves for frequency recovery (secondary regulation);
- replacement reserves (tertiary regulation);

2) maintaining the parameters of reliability and quality of electricity in the UES of Ukraine, namely:

- voltage and reactive power regulation services;
- services to ensure the resumption of the functioning of the UES of Ukraine after systemic accidents.

The market rules may provide for other auxiliary services to ensure the regulation of frequency and active power, maintain the balance of power and energy in the UES of Ukraine and maintain the parameters of reliability and quality of electricity in the UES of Ukraine.

The transmission system operator provides the payment administrator with information about the volumes and prices of the ancillary services purchased by him, as well as about actually provided auxiliary services for calculating the relevant payments. Information on the volume and cost of purchased auxiliary services is subject to release by the transmission system operator in the manner prescribed by market rules.

After analyzing the possibilities of the auxiliary services market and the balancing market, we can conclude that with the help of these market mechanisms it is possible to solve part of the problems of ensuring the reliability of electricity supply, without the need for technical means to work and disconnect consumers.

2.2 Analysis of the capabilities of electricity consumers in regulating the frequency in the network

According to [12], electricity companies must inform local executive authorities and consumers about the electricity supply situation. Consumers are informed about the need to apply a set of measures to limit and cut off electricity by the Ministry of Energy and Coal Industry and electric power companies through the media. Thus, restrictions on the zones of electricity systems are put into effect by the order of the Director (Chief Dispatcher) of NPC Ukrenergo in coordination with the Ministry of Energy and Coal Industry of Ukraine.

In the zone of the electricity system, the restrictions are put into effect by the order of the director (chief dispatcher) of the electricity system in the volumes established by NPC Ukrenergo. In case of impossibility of obtaining the required volumes of power and electricity due to insufficient capacity of subordinate electricity transmission lines, autotransformers, or unacceptable reduction of the voltage of the schedule, restrictions are introduced by the electricity system independently with the obligatory notification of the management of NPC Ukrenergo. In case of exceeding by the enterprise of the electric power industry of a given mode of electricity consumption, determined, and proved to the enterprise by the electric power industry in accordance with regulatory documents, the restriction schedules are put into effect by order of the director (chief engineer) of the electricity company with the obligatory notification of the electricity system.

Subject to the operation of the electric power system (electricity company) in an isolated mode, the schedules are put into effect by the director or chief dispatcher of the electricity system (director or chief engineer of the electricity enterprise) independently.

At the disposal of the graphs of the restriction indicates the amount of electrical power (MW) or electrical energy (thousand kWh per day), which is subject to restriction, indicating the start and end time of the restriction.

The time of commencement of the introduction of restriction schedules is determined in such a way that the orders for their introduction can be transferred by the electricity company directly to the duty personnel of the consumer (telephony, fax or e-mail) no later than 1 hour before the start of the restriction with the obligatory indication of the reasons for the use of these schedules.

Also, in case of an unexpected occurrence in the UES of Ukraine (electric power system) of an emergency shortage of electrical power, the commissioning of the ESS, SESS, disconnection with buttons (keys) SALD are carried out on the command of the duty dispatcher of NPC "Ukrenergo" or the dispatcher of the electric power system. In case of non-compliance by the enterprise with the electricity industry of a given mode of consumption of electric power in the conditions of the deficit balance of the UES of Ukraine and the low efficiency of the applied means of regulating power consumption by order of the director or chief engineer of the electricity enterprise, the ESS (from the first to the fifth stage) is put into operation with the obligatory notification of the dispatcher of the electric power system, who in turn informs the dispatcher of NPC Ukrenergo.

The duration of the interruption in the power supply of consumers during the shutdown according to the schedules (ESS or SESS) of power lines and transformers, as a rule, should not exceed 2 hours, and in agreement with local executive authorities may be a longer period. After this time, in the presence of an unused ESS reserve and the lack of normalization of electricity supply in the UES of Ukraine, feeders and transformers disconnected according to the schedules should be included after disconnecting the corresponding load volumes from the unused reserve. If necessary, a long-term load reduction should be put into effect by the EPSLS. In case of a significant shortage of generating power, in case of threat of collapse of the UES of Ukraine and mass operation of AFU, multiple shutdowns of the same lines (feeders) for ESS with a break between shutdowns for 1 - 2 hours is allowed.

2.3 International practice of frequency control through economic mechanisms.

2.3.1 U.S. experience in regulating the frequency of the power system

World practice shows the idea of a new electricity market introduced in Ukraine in 2017 is not new and has already been used in different countries of the world, for example in the USA.

Article [13] describes that the service we call "frequency control" usually starts a few minutes after the frequency deviation event, after the secondary frequency control has started. In those areas that have restructured the utilities sector and created competitive markets, frequency regulation is usually procured by system operators through an auction process in advance, such as the day ahead and the real-time energy market. The market operator (e.g., PJM) announces how much frequency control capacity is required and generating companies (generators) submit proposals to be able to ensure this frequency adjustment.

In most electricity markets, offering frequency regulation to a network operator means that the generator is ready to increase or decrease output (known as "upward regulation" and "downward regulation") by a certain amount. (The ERCOT market in Texas works a little differently, where there are separate markets for upward regulation and downward regulation.) This means that the generator, at the same time, removes power from the energy market a day in advance / in real time and seeks to be able to produce a certain amount of energy. Thus, the generator will not be able to offer more than 95 MW of its capacity in the energy market "day in advance"/in real time and would make sure that at least 5 MW was free in the energy market "a day in advance"/in real time.

The adjustment fee has two components. First, generators are paid for the power they devote to providing regulation. This is sometimes referred to as a "possibility" of price and takes up units of $ per MW of power.

For example, take our same generator that provides 5 MW of regulation. The generator is sent to produce 50 MWh of energy through the market in real time at a price of $ 10 per MWh. Due to the event of deviation of the frequency of the generator, it is proposed to produce an additional 2 MW of power within 10 minutes.

1. Energy market revenue: 50 MWh * $10/MWh = $500
2. Ability to adjust: 5 MW * $5/MW = $25
3. Adjustment performance: 2 MW * (1/6 hour) * $10/MWh = $3.33
4. Total revenue: $528.33

So, we can conclude that the market for regulating the frequency of the United States is generally similar to the BM of Ukraine, which once again confirms its effectiveness.

2.3.2 Czech Republic's experience in regulating the frequency of the power system

Another option of international experience in the economic regulation of the frequency of the power grid is one of the energy laws of the Czech Republic.

According to this law, the order on emergency provides for the possibility of limiting the supply of electricity or changing its selection from the system using the following measures:

1) implementation of the plan of restrictions on electricity consumption (the so-called regulatory plan, hereinafter: the restriction plan),

2) termination of supply to end consumers disconnected by network operators and disconnection of part of the transmission system or distribution systems for:

- disconnection plan,
- frequency change plan, by immediately disabling part of the transmission or distribution systems to the extent necessary to balance the part of the network that is prone to accident,
- changes in the supply of electricity to the network by the electricity producer at the direction of the OSP or DSO dispatcher.

Also, this energy law prescribes a plan of outages, which provides for 7 scenarios, according to which restrictions are imposed on electricity consumers who study in seven categories. Scenarios 1-7 are supplemented by a baseline scenario (normal situation) and a warning that signals non-compliance with the criteria for reliable operation of networks and the possibility of restrictions on electricity supply. The restriction of consumption under the restriction plan does not apply to electricity consumption for own needs related to electricity production and heat supply.

Disconnection plan:

The plan spells out 10 scenarios of outages (21-30).

Frequency change plan:

The plan provides automatic actions for

1. prevention of the threat of large-scale accidents,
2. stabilization of the frequency after the accident at the level that ensures the technical safety of the manufacturer's and the consumer's installations
3. to restore the frequency of 49.8-50.2 Hz.

Tables 2.1 and 2.2 describe scenarios for restrictions and disconnection of consumers in different situations.

Table 2.1 Scenarios of restrictions in case of emergency

	Scenarios	
1	Reducing the power received from the power plant by disabling or blocking the inclusion of selected equipment controlled remotely (collective remote control) or other technical means of consumption control.	
2	Reducing the power received by means of the operator's technical means to 1 hour after the announcement of the scenario unless a longer period has been set. Reduction of each consumer enrolled in category 2.	
3	Reduced power. Up to 30 minutes after the scenario is announced.	15%
4	Reduced power. Up to 1 hour after the script was announced, unless a longer time was set.	15%
5	Reduced power. Up to 1 hour after the scenario is announced.	15%
6	Reduced power. Up to 2 hours after the script was announced, unless a longer time was set.	15%
7	Reducing the power of all end users to a minimum level of security up to 1 hour after the scenario is announced. In the case of equipment where it is impossible to reduce the power received to the required level for up to 1 hour, a temporary shift (clock) is set to achieve it. The minimum level of safety is understood as the lowest power obtained from an electrical installation, which after the end of production is necessary for the safety of equipment, as well as in terms of environmental impact and employee safety.	

Table 2.2 Scenarios of outages in case of emergency

<table>
<tr><td rowspan="2">Scenarios</td><td colspan="4">Power outage (relative to the annual maximum load of the distribution system over the past 12 months)</td></tr>
<tr><td>%</td><td>Comments</td><td>Total</td><td>Announcing the scenario</td></tr>
<tr><td>21</td><td>2,5</td><td>After the scenario is announced, 21 separate parts of the transmission or distribution systems are disconnected so that the consumption limit does not exceed 2.5% of the annual maximum load of the corresponding distribution system.</td><td rowspan="4">12,5%</td><td rowspan="4">Scenarios 21-30 cannot be declared at the same time. The percentage of outages is coordinated by TSO and DSO dispatchers, who also disable and activate. When you declare a scenario, you specify the area in which you enter the opt-out and how long it will take. In cases where it is not possible to specify the duration of…</td></tr>
<tr><td>22</td><td>2,5</td><td>-</td></tr>
<tr><td>23</td><td>2,5</td><td>-</td></tr>
<tr><td>24</td><td>2,5</td><td>-</td></tr>
</table>

Continuation of Table 2.1

<table>
<tr><td>25</td><td>2,5</td><td>-</td><td></td><td rowspan="6">…the shutdown, when the command announces this disconnection, it is determined additionally, but not later than 2 hours after the command to disable the end user equipment.</td></tr>
<tr><td>26</td><td>Up to 17.5</td><td>After scenario 26 is announced, the selected parts of the transmission or distribution systems are disconnected so that the consumption limit does not exceed 17.5% of the maximum annual load of the corresponding distribution system.</td><td rowspan="5">37,5%</td></tr>
<tr><td>27</td><td>5</td><td>-</td></tr>
<tr><td>28</td><td>5</td><td>-</td></tr>
<tr><td>29</td><td>5</td><td>-</td></tr>
<tr><td>30</td><td>5</td><td>-</td></tr>
</table>

The outage scenarios described above may also be a good option for solving the imbalance problem but are tougher for the end user. Although given that the need to localize the problem and solve it as soon as possible with the subsequent re-switching on of power, as for me is a good option, in a short time of disconnection in production may not happen crushing consequences for the equipment, and it will again be able to return to work.

Conclusions to the second section

This section analyzes the economic tools for solving the problem of energy system reliability. In particular, the electricity markets were analyzed: the market of bilateral agreements, DAM, IDM, BM, the market of ancillary services for the possibility of attracting electricity consumers to reduce power shortages. The international experience of the Czech Republic and the United States in regulating the frequency of the power system is analyzed.

Insufficient level of influence of the modern methodological base on the consumer is established, in the part of motivating him to manage the power deficit in the UES of Ukraine.

The need for further methodological developments in terms of attracting consumers by providing him with certain discounts on electricity tariffs.

SECTION 3

DEVELOPMENT OF METHODOLOGICAL PLEDGES FOR THE FORMATION OF TARIFFS FOR INTERRUPTION OF POWER SUPPLY

3.1 Problems of electricity shortage and ways to reduce it

One of the problems that the united power system of Ukraine constantly faces is a significant shortage of electrical power, especially in the autumn - winter period. This deficit does not decrease, despite a sharp reduction in electricity consumption in industry, because this is primarily due to chronic fuel shortages in power plants for various reasons, unsatisfactory condition, as well as an increase in the accident rate of generating equipment. It should be expected that in the foreseeable future, even in the conditions of normal fuel supply, the shortage of electricity in the power system will continue, as the demand for electricity will gradually begin to grow, and a significant part of generating capacities, as already noted, has exhausted its resource, and needs to be replaced. As a result of the current situation, the energy industry of Ukraine is practically unable to provide continuous and high-quality electricity to consumers.

Obviously, the energy sector of our state needs radical changes in the structure of its generating capacities. Therefore, the construction of new and reconstruction of existing power plants, of course, is the main direction of the energy sector's exit from a difficult situation. Actions in this direction should begin as soon as possible. However, the implementation of the necessary measures towards the creation of maneuverable power generating capacities requires significant funds and, equally important, considerable time, that is, this path does not lead to a quick solution to the problem [14].

In the current situation, the only real measures to prevent systemic accidents are forced restrictions on the demand for electricity and periodic disconnection of consumers. This leads to significant damage to the country's economy, as well as creating significant inconvenience for the population.

However, with the formation and development of a new electricity market, it is gradually becoming possible to attract consumers to maintain the necessary modes of electricity use and there is a need to stimulate a large number of consumers to participate in balancing the power system.

In market conditions, with the exception of emergency situations, only economic methods should be used [15], encouraging consumers to participate in improving the level of reliability of the power system, which today, as mentioned above, is largely determined by the state of generating equipment.

As the experience of foreign countries presented in section 2 shows, the solution to the problem of electricity shortages in the power system should be sought in the cooperation of energy and consumers. One way to solve this problem is to create the relevant economic interest, i.e., to provide certain benefits for the payment of electricity to consumers who agree in advance to limit or completely cut off their electricity load in the event of a shortage of electricity in the grid. According to the current structure of the energy sector of Ukraine, such advantages are established by the new electricity market for those wholesale electricity consumers who agree to participate in improving the reliability of the power system, and these wholesale consumers, in turn, for relevant electricity consumers.

The establishment of the level of such benefits for the purchase of electricity for wholesale electricity consumers can be based on an assessment of the level of reliability of the generating part of the combined power system, as well as on determining the cost savings of the Energy Market while reducing the electricity load of consumers in case of electricity shortage in power systems [16].

But when using this approach to the formation of preferential tariffs, it is also necessary to consider new maneuverable power plants and rapidly developing RES. And it will be difficult to consider their impact on the future formation of tariffs. As for me, the main problem of the existing market of auxiliary services and the balancing market is that information about the need for balancing is obtained according to each day, and the price for this is formed according to what amount of power is needed for balancing right now. Consumers, in my opinion, are not very interested in participating in balancing the power system at a certain point in time for which they may not be ready. And if you develop a basic tariff for balancing, and an additional one for an additional amount of power at a certain point in time, it will be more convenient for consumers to count on the fact that at a certain point in time they have the opportunity to allocate the pre-maneuverable power for balancing needs, and not to think about whether it will be profitable for them now to stop certain production units for the sake of balancing needs.

3.2 Assessment of the reliability of the generating part of the power system

3.2.1. Overview of the methods used to determine reliability indicators

Electric power systems (EPS) are dynamic systems of complex type, consisting of many components (generators, transformers, power lines, switching devices, etc.). At the same time, the complexity of the system is determined not only and not so much by the number of elements, but by the presence of a connection between them. For EPC, complexity is determined by the fact that all its elements are functionally connected by the unity of the process of production, distribution, and consumption of electrical energy [17].

For complex systems, the concept of reliability is complex, characterized by several properties (reliability, durability, maintainability, stability, survivability, handling, safety). Reliability is understood as a property of an object (it can be both the system itself and its constituent elements) to perform specified functions in each volume under certain operating conditions. The reliability of EC depends on various factors. As noted in [17] the decrease in the reliability of the EU arises as a result of:

• failures of the elements that make up the system (main and auxiliary equipment, equipment and devices of control systems);

• disruptions in the supply of fuel to thermal power plants (TPPs) and reduced fuel quality;

• reduction of water supply of hydroelectric power plants (HPPs);

• errors of operational personnel.

Along with these reasons, it is also possible to consider deviations in the operating conditions of the power plant from the expected (calculated): exceeding the actual electricity consumption (both in power and electricity) over the estimated one; delays in the introduction of equipment (generation, network, manager). Deviation of operating conditions from the calculated ones is not a manifestation of unreliability, but technical imperfection of the system, but this factor is convenient to consider along with the reasons for the decrease in reliability, implying that the means of increasing it can simultaneously increase the level of technical perfection of power supply. [17].

The action of factors that reduce the reliability of the ES is an objective reality and can be reduced only through appropriate targeted actions, but not eliminated, since it is obvious that absolute (100%) reliability of electricity supply cannot be achieved.

Compensation for factors that reduce the reliability of the ES is achieved [17]:

1. selection of the appropriate "design" of the power plant (configuration of the electrical network, primary switching scheme and own needs of power plants and substations, structure of generating capacities, etc.);
2. improving reliability and improving design and technical characteristics (for example, maneuverability - for generating units) of equipment;
3. reservation at all levels of the system (production, conversion, transmission and distribution of electricity, control system), including ensuring energy reserves (improving the reliability of fuel supply to thermal power plants and its quality, creating water reserves in hydropower tanks);

4. selection of the structure and parameters of system management tools;

5. improving the organization of the power plant, including improving the system of preventive maintenance of the main equipment, equipment and apparatus of the control system;

6. quality of work of operating staff.

One of the main ways to improve the reliability of the ES is to reserve, and it is aimed at partial compensation for all the above reasons that reduce the reliability (and technical excellence) of the ES. [17].

Uninterrupted power supply of individual units of the power supply system (PSS) depends on almost all elements of PSS. If we assume that each element can be in one of two states - working, idle (the element is disabled), then the total number of states of PSS is 2^m, where *m is* the number of elements of PSS. Realistically, the number of significant states of the PSS system is even greater due to the states of partial disability of the elements. it is necessary to consider each of the states of PSS and assess its impact on the state of partial disability of the elements. reliability indicators of system nodes. The discreteness of the space of the state of PSS is determined by the complexity of the procedures for calculating reliability indicators.

Methods for calculating the reliability indicators of PSS according to the mathematical apparatus used can be divided into two classes: analytical and statistical modeling, and by reproducing the properties of elements - into methods that consider individual random states, and methods that consider the properties of the random process of functioning of the elements of PSS [17].

Methods of statistical modeling allow you to most fully consider those properties of PSS that have not yet been described by mathematical models [17].

The use of random processes to describe the behavior of PSS elements is associated with a large amount of memory to store information about a random process. [17]. These include:

- logical and probabilistic (E.A.Losev, I.A.Ryabinin, etc.);
- logic-analytical (Y.B.Guk, E.A.Losev, A.V.Myasnikov and others);

- tabular-logical (F.I.Synchugov, V.G.Kitushin and others);
- flowchart method (P.I. Grusnsky, V.I. Edelman, etc.);
- method of minimum tracks and sections (V.V. Zorin, Y.A. Fokin, etc.);
- method of generalized equivalence (D.A.Arzamatsev, V.P.Oboskalov, A.S.Dulesov, O.M.Kotov).

Each of these methods has its advantages and disadvantages, but they all have a common formulation of the problem. In almost all methods the analysis of probabilistic states of the system is carried out. These general properties are quite fully described by the method of state spaces and tabular-logical method. These methods can be chosen to describe and illustrate the procedures for calculating the reliability of complex closed PSS.

To assess the reliability of the system using the state spaces method, it is necessary to first describe the system with its states and possible transitions between these states, and then describe the demand for electrical load in the ES. [17].

According to this method, the general state of the system is determined by the state of each element of this system: the element either works or fails, undergoes forced repair, or is in some other state. If the state of one of the elements changes (for example, a or b in Figure 3.1), then the system also moves to a new state. Figure 3.1) forms the space of states. The demand for electricity can be represented by a forecast graph of the load of the combined energy system. $\boldsymbol{A} = \{\boldsymbol{A}_0, \boldsymbol{A}_1, \boldsymbol{A}_2, \boldsymbol{A}_3\}$

The main advantage of this method is the possibility of using the Markov model [18,17] to describe the process of switching the system from one state to another. The condition for the applicability of this model is that the probability of transition from one state to any other should not depend on the prehistory of the system, that is, on the states in which the system was previously located.

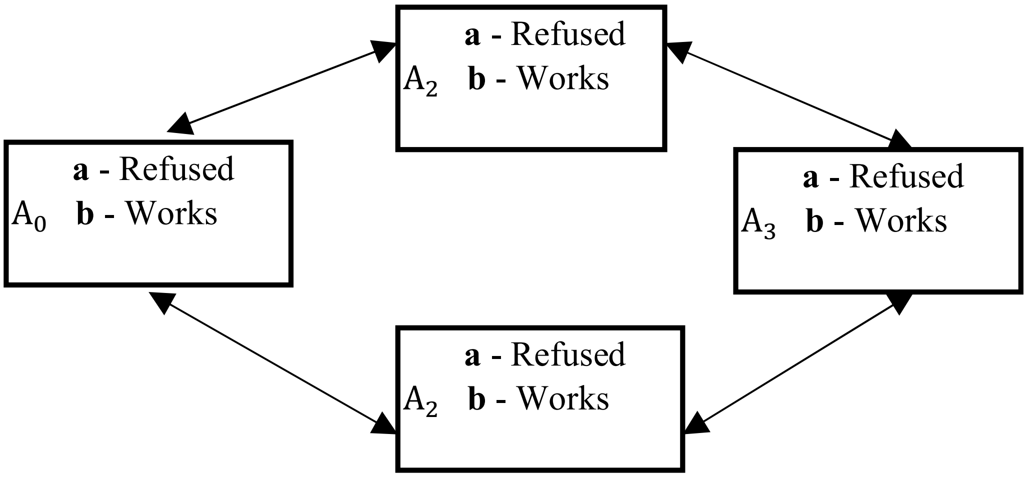


Figure. 3.1. Diagram of the states of two independent elements a and b

The main scope of application of the state space method is the calculation of the characteristics of the reliability of repair systems.

The model of possible states of the system does not reflect all the real properties of the electricity system. In other words, it is assumed that the electrical network is capable of transmitting energy from sources to consumers in any switching scheme of generating units and any configuration of the electrical network without losses, overloads and voltage drops, and, consequently, the system works successfully if the available power of generators is sufficient to cover the loads of consumers. Thus, the criterion by which the successful operation or failure of the system is determined at any given time is that the power of generators may exceed the load capacity, can be equal to the load capacity and may be less than the load capacity; in the first two cases, the system works successfully, in the latter case the system fails [18,17].

3.2.2.Modeling of the states of the generating part of the power system

Modeling of the states of the generating part of the power system, based on the method of state spaces, is a rather voluminous and extensive task [19,18].

• The service life of a generating unit cannot usually be described as simply as it is for an element with two states: "in operation" - "in emergency repair".

• generating units - complex engineering devices; in addition to complete failures, they can sometimes go into a state of partial failure, continuing to operate at low power.

• units are periodically stopped intentionally for preventive repairs and maintenance.

Of course, you can use a model with a large number of states to describe the state of partial downtime of generating units (states with degraded parameters). However, the degree of accuracy required in the calculations for planning the reserve of generating capacity is usually achieved when using a model with two states.

When studying generating capacities by the state space method, the main value to be determined is *the established range,* which is necessary so that the risk of incomplete coverage of the required load at any time does not exceed a certain given value.

When studying generating capacities by the state space method, the main value to be determined is *the established range,* which is necessary so that the risk of incomplete coverage of the required load at any time does not exceed a certain given value.

The most important initial values for analyzing the reliability of the generating part of the system, which sufficiently reflect its condition, are the installed power of generators and the coefficients of load-bearing readiness of the units. [17].

Based on the data on the number of units in operation and their installed capacities, the total installed capacity of power system generators is determined:

$$P_{total} = \sum_{i=1}^{n} P_i \tag{3.1}$$

where $\mathbf{P}_i$ - installed power of the i-th generator, kW;

n - number of generators running.

As already mentioned, when building a model of the space of the state of the power system, we believe that each individual unit can be in one of two states - working and non-working (the unit is disconnected). 3.1). Moreover, it is assumed that the states of the units are independent of each other, that is, failures and repairs of each of the units do not depend on failures and repairs of other units.

The operating power $\mathbf{P}_x$ of some state of the power system x can be determined by the formula:

$$P_x = P_{total} - P_{x.discon.} \tag{3.2}$$

where, $\mathbf{P}_{x.\mathbf{discon.}}$ total installed capacity of "disconnected" units of some state x power system, kW.

The total installed power of the "disconnected" blocks in some state x can be determined by the formula [16]:

$$P_{discon.} = \sum_{j=i}^{k} P_j \tag{3.3}$$

provided that the $i = 1 \ldots n$ i $k = i \ldots n$.

where i and k are the serial numbers, respectively, of the initial and last shut-off units for some possible state of the power system.

The model built at this stage is a set of possible states of the energy system (x), for which the corresponding operating capacity of $\mathbf{P}_x$ is determined, as well as the number of "failed" units of the power system in its state.

The readiness factor of the i-th $\mathbf{K}_{ri}$ unit used in this method is defined as the ratio of the duration of the operational readiness of the unit during the year to the total number of hours per year. Accordingly, the coefficient of forced downtime of an individual unit (for example, the i-th) is determined by the formula:

$$K_{Fi} = 1 - K_{Ri} \tag{3.4}$$

Thus, using the above coefficients, it is possible to determine the probability **of** $\mathbf{B}_g$ of the state g ES, in which g blocks of their total number n work simultaneously.

$$B_g = K_R^g \cdot K_F^{n-g} \tag{3.5}$$

To simplify further calculations, we combine states with the same total power of the remaining units in operation and for each state of the power system determine the overall probability that the total load of consumers will exceed the available capacity of the units. When combining the state *x* and *y*, which leads to a new state *z*, the following relationships are valid:

$$\boldsymbol{P}_Z = \boldsymbol{P}_X = \boldsymbol{P}_Y\,;\ \boldsymbol{B}_Z = \boldsymbol{B}_X + \boldsymbol{B}_Y \tag{3.6}$$

where $\boldsymbol{P}_Z, \boldsymbol{P}_X, \boldsymbol{P}_Y$ total operating power by condition *x, y, z*, kW;

$\boldsymbol{B}_X, \boldsymbol{B}_Y, \boldsymbol{B}_Z$ - probability of appropriate states *x, y, z*.

The proposed approach to building a model of possible states of the generating part of the power system, even using two states of power units, is a rather laborious task. First of all, this is due to the fact that the system contains generators with different installed power and accessibility factors. Therefore, the task of constructing a model of possible states of the generating part of the power system can be greatly simplified using equivalence methods. [16].

Using [19] we determine the value of the readiness coefficients of an equivalent unit and forced downtime by formulas:

$$K_R^E = \frac{\sum_{i=1}^{n} K_{Ri} \cdot P_i}{\sum_{i=1}^{n} P_i} \tag{3.7}$$

$$K_F^E = 1 - K_R^E \tag{3.8}$$

It is assumed that the number of equivalent units is equal to[19] the actual number of units.

$$n^E = n \tag{3.9}$$

The installed power of one unit is determined by the formula:

$$P^E = \frac{\sum_{i=1}^{n} P_i}{n^E} \tag{3.10}$$

Using the binary law of distribution, as well as the value of the readiness coefficients of an equivalent unit and forced downtime, we determine the probability of simultaneous working state of *g* aggregates with *n* according to the formula:

$$B_g = C_n^g \cdot K_R^{E(g)} \cdot K_F^{E(n-g)} \tag{3.11}$$

Where $C_n^g = \dfrac{n!}{g! \cdot (n-g)!}$.

The proposed approach to building a model of possible states of the power plant is the first stage of assessing and determining the installed capacity of the power system.

However, it should be noted that from a practical point of view, the use of installed power to calculate reliability indicators is not entirely correct. This is primarily due to several technical conditions that do not allow the use of the installed capacity of generating equipment. Thus, when calculating this technique, it is most advisable to work with the average maximum operating power of generators. And in the end, let's talk about *the maximum working capacity reserve of the* power system.

As already noted, the coefficient of readiness of units for load transfer is one of the main parameters of constructing a model of possible states of the generating part of the power system. In the model under consideration, the accessibility factor is determined based on statistical operational data on the operation of power units.

3.2.3.Modeling of coverage of the total electrical load of the power system

Planning of power reserves and operational management of power system modes is impossible without preliminary analysis and assessment of expected loads and power consumption modes. Therefore, the initial data for the construction of the load model are the hourly values of electricity consumption in the unified power system, projected on the characteristic days of each month of the planned year, minus the load of indoor nuclear power plants and hydroelectric power plants.

The predicted hourly load values of the power system should be arranged in descending order, that is, the highest hourly values are located in the first place of the ordered load series. At the same time, the same hourly load values are combined according to the following rules:

$$P_{i.j} = P_i = P_j ; t_{i.j} = t_i + t_j \tag{3.12}$$

where the hourly load of the power system after combining $P_{i.j}$ loads of i-th and j-th, MW;

$t_{i.j}$ - the duration of maintaining the constant load of the power system at the level of $P_{i.j}$;

P_i, P_j - the value of the load of the power system in the i-th and j-th hours of the day. MW;

t_i, t_j - conditional duration of preservation of the unchanged load of the power system (one hour).

After ranking the values of the power system load and combining the same loads, a step-by-step graph of the load duration is built, which is a model for covering the electrical load of the combined power system in the planning year. This step chart of the power system load can be replaced by a continuous function L describing it (Figure 3.2).

3.2.4. Assessment of the probable non-supply of electricity and the average electricity shortage of the power system

For each state of the power system in which the total operating power of generators is $\mathbf{P_j}$, based on the load duration graph (Fig.3.2), it is possible to determine the time $\mathbf{t_j}$, during which the projected load of the power system will exceed the operating capacity of power units. Thus, the expected undersupply of electricity to consumers (*E*) in such a state of the power system, corresponding to the total operating capacity of $\mathbf{P_j}$ generators, is characterized by a shaded area of $\mathbf{D_j}$ (Fig. 3.2) and is determined by the formula:

$$E = \sum_j B_j \cdot D_j \tag{3.13}$$

Where $D_j = \int_0^{t_j} (L - P_j) dt$ a patched area in figure 3.2;

L - function that describes the projected schedule for covering the load of the power system;

B$_j$ - probability of loss of power in the j-th state of the power system.

When using a stepped schedule for covering the load by units of the power system, the area **D$_j$** is determined by:

$$D_j = \sum_{i=1}^{k} P_i \cdot t_i \tag{3.14}$$

where k - the number of stages of constant load of the power system available on the graph (figure 3.2) within the time interval k;

P_i - power of the i-th degree of load of the power system, which refers to the time interval **t$_j$**, MW;

t_i - load duration P_i.

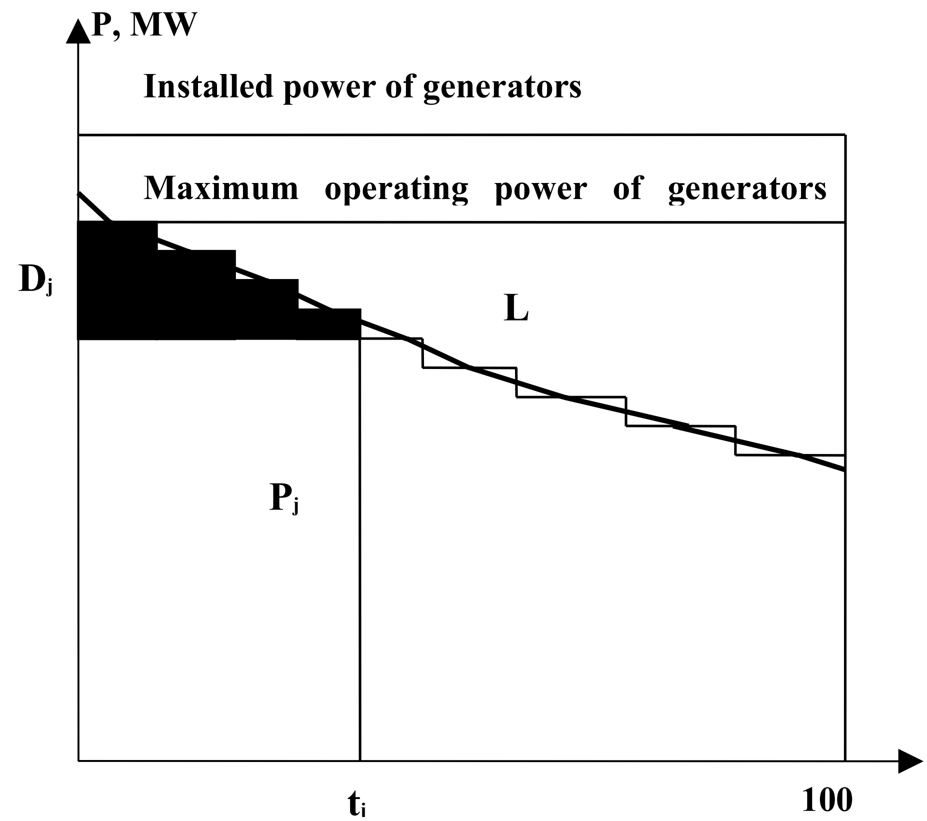


Figure 3.2 Ordered power system load schedule

Determination of the probability of loss of electric load is based on the calculation of the probability of loss of load by the LOLP power system (Probability of load loss) or the probability of system failure [18,16], which is the general probability of the state of the generating part of the power system, in which its load will not be covered, and is determined by the formula:

$$\boldsymbol{LOLP} = \sum_j \boldsymbol{B}\,[\boldsymbol{P} = \boldsymbol{P}_j]\,\boldsymbol{B}\,[\boldsymbol{L} > \boldsymbol{P}_j] = \sum_j \frac{\boldsymbol{B}_j \cdot \boldsymbol{t}_j}{100} \tag{3.15}$$

At the same time, the probability of loss of load by the power system, expressed in hours per year, is calculated by the formula:

$$\boldsymbol{LOLP}_o = 8760 \cdot \boldsymbol{LOLP} \tag{3.16}$$

The calculation of the value of the average power deficit is based on the determination of the average power that can be lost by the power system for a time equal to $\mathbf{P}_{\mathbf{aw.s.}}$ value $LOLP_o$ (power shortage) [16]. The specified average power is calculated based on the value of the expected undersupply of electricity E, which corresponds to the overall probability of loss of electrical load by the power system:

$$P_{av.s} = \frac{E}{LOLP_o} \tag{3.17}$$

Considering the likelihood of loss of load, to ensure reliable and trouble-free operation of the power system, either an appropriate reserve of generating capacities must be created, or it should be possible to reduce the load of consumers by the amount of $\mathbf{P}_{\mathbf{aw.\ s}}$ in case of electricity shortage.

3.3.Justification of the level of discount on consumer participation in reducing the electricity shortage of the power system

The task of reducing the electricity shortage of the power system and covering the demand for electricity at the level of the Energy Market can be solved by one of the proposed options [16].

The first option:

• Full redundancy of expected electricity loss.

• Power supply according to the initial schedule.

The second option:

• Reduction of power reserve by the amount of the agreed limited load;

• compensation for underestimation of electricity during the day at low load of the power system.

The proposed approach to establishing a discount on the electricity tariff for consumers involved in reducing the electricity shortage of the power system is since in the process of its use, the Energy Market will receive savings from the use of a schedule for limiting electricity consumption. [16]. It should be noted that the economic effect obtained during the implementation of this approach is primarily due to the following factors:

- fuel economy on reserve units;
- reduction of working hours of power units at idle.

Таким чином, очікувана річна економія енергоринку ΔD_o може визначатися за формулою:

$$\Delta D_o = \Delta D_{hr} + \Delta D_E \tag{3.18}$$

where $\Delta Д_{xx}$ - annual fee to units for hot reserve, million UAH;

$\Delta Д_E$ - annual savings of the energy market when compensating for insufficient electricity supply during the day with a reduced load of the power system, million UAH.

Considering the fact that calculations on the establishment of a discount on tariffs for consumer participation in reducing the electricity shortage of the power system are carried out:

- once a year when setting a discount for the next year;
- twice a year with the establishment of seasonal discounts to tariffs (winter and summer);

Then it is most advisable to act in these cases with average values.

The determining factor in the proposed approach is the definition of a block fee for finding blocks in a hot spare. According to the Rules of the energy market, the annual fee per unit for a hot reserve can be determined by the formula:

$$\Delta D_{hr} = \sum_{i=1}^{N_p} \overline{Z}_{hr.i} \cdot 8760 \tag{3.19}$$

де $\Delta Z_{hr.i}$ - the average cost of keeping the I-th block idling, a thousand hryvnias / hour;

N_p - number of blocks in hot spare.

Average idling costs specified in the formula (3.19), can be determined by the formula:

$$\overline{Z}_{hr.i} = \frac{\sum_{k=1}^{N_p} Z_{hr.k}^{p}}{N_{,k'}^{p}} \tag{3.20}$$

де $Z_{hr.k}^{p}$ - the cost of downtime for each stage of the installed capacity of the units, a thousand UAH / hour;

N_p - number of units at one stage of installed power.

It should be especially noted that the power shortage in the power system occurs during the hours of maximum loads [16]. Naturally, reducing the load of the enterprise, even agreed, invariably leads to a decrease in production volumes. Thus, the proposed methodology should provide for the possibility of compensation to the electricity company during the hours of minimum loads of the power system (hours of night failure). The annual energy market savings obtained in this way can be determined by the formula:

$$\Delta D_E = (\overline{C}^{wh} - \overline{C}_{fail.}^{\max}) \cdot E_{agreed} \tag{3.21}$$

де $\overline{C}^{wh}$ - average wholesale purchase price of electricity, UAH/kWh;

$\overline{C}_{fail.}^{\max}$ - the maximum price of the system for the period of load failure, UAH / kWh;

E_{agreed} - cost of agreed electrical capacity per year, MWh.

One of the important stages is the determination of the average price values used for financial settlements in the energy market. The average wholesale purchase price of electricity for the year can be determined on the basis of statistics of the Energy Market according to the formula:

$$\overline{C}^{wh} = \frac{\sum_{p=1}^{8760} C_y^{wh}}{8760} \tag{3.22}$$

where - C_y^{wh} price of electricity for each hour of the year, UAH/kWh.

In turn, the average wholesale purchase price of electricity per day is determined by the formula:

$$\overline{C}_{wh} = \frac{\sum_{p=1}^{24} C_y^{wh}}{24} \tag{3.23}$$

The marginal price of the system for the period of load failure can be determined by the formula:

$$\overline{C}_{short.}^{\max} = \frac{\sum_{p=1}^{N_{short.}} Ц_{short.}}{N_{short.}} \tag{3.24}$$

where $C_{short.}^{\max}$ maximum price of the system in the hours of power system load shortage, UAH / kWh.

As noted above, it is assumed that the lack of electricity can occur during the hours of maximum loads of the power system. Therefore, the value of the agreed limited electrical power during the year can be determined by the formula:

$$E_{\text{a}greed} = T^{hr} \cdot P_{short.agreed} \tag{3.25}$$

where - T^{hr} the average value of the required part of the equipment in the hot reserve (we take equal to the number of hours of maximum load of the power system);

$P_{short.agreed}$ - the value of the agreed limitation of electricity to consumers in case of a shortage of electricity of the power system.

If any (n-a) energy supply company agrees to limit its electrical load by the amount of $P_{short.agreed}^{n}$, in case of energy shortage of the power system, these energy supplying organizations provide the Energy Market with annual savings in the cost of purchasing electricity from generating companies in the amount of:

$$\Delta D_n = \frac{\Delta D_o}{P_{short.agreed}} \cdot P^n_{short.agreed} \tag{3.26}$$

Using a similar approach to determining the annual cost savings for the purchase of electricity from wholesale consumers (Oblenergos, independent electricity suppliers, etc.), it is possible to establish a discount on electricity payments directly for consumers who agree to limit their load in case of a shortage of electricity to the power system.

3.4 Directional distance function and shadow pricing of power interruptions

It can be assumed that the power supply has two main states: continuous supply (supply of energy), as well as interrupted supply (energy is not supplied). To estimate the cost of not supplied energy, you can draw an analogy with the function of the directional distance. The directional distance function has the desired (or good) and undesirable (or bad) results [20]. With the directed distance function, the shadow price method will be used to estimate the cost of power breaks. The shadow price of poor results is presented in the reference [20]. Methodology provides that the production of good results includes the production of poor results. The shadow price can also be obtained using the distance function [20]. The main advantage of the directional remote function over the distance function is that it simultaneously allows you to expand good output and reduce bad outputs. Regarding electricity services, both outstanding sales days (DSOs) and the authorities want to reduce the frequency and duration of breaks, as well as increase the total amount of energy supplied to consumers. As a result, it is more convenient to accept the directed distance function to estimate the shadow prices of the value of the lost load, or the value of one minute of break. Thus, the result of shadow pricing will lead to the cost of reducing one unit of bad products (lost customer minutes) and increasing one unit of good production (supplied energy) at the same time in terms of operating costs. The main features of the directional distance function are as follows:

Suppose there are N inputs, M good outputs and J bad outputs, then inputs (x), good inputs(y) and bad outputs (b) are indicated respectively:

$$x = (x_1,\ \dots\ x_N) \in R_+^N \tag{3.27}$$

$$y = (y_1,\ \dots\ y_N) \in R_+^M \tag{3.28}$$

$$b = (b_1,\ \dots\ b_N) \in R_+^J \tag{3.29}$$

Let P(x) denote production technology [21], where

$$P(x) = \{(y,b):\ x\ may\ come\ from(y,b)\} \tag{3.30}$$

The function of the directional output distance serves as a functional representation of the technology. Production technology P(x) is represented by the function of directional distance D_o [21] let g = (g_y, g_b) — directional vector, a β — maximum expansion of good exits in the direction of g_y and minimal reduction of bad exits in the direction of g_b , then D_o it is defined as:

$$\vec{D}_0(x, y, b; g_y, g_b) = \max\{\beta : (y + \beta g_y, b - \beta g_b) \in P(x)\} \tag{3.31}$$

$$\vec{D}_0(x, y + a g_y, b - a g_y, g) = \vec{D}_0(x, y, b; g) - \alpha \tag{3.32}$$

Purpose is to increase the amount of energy supplied to customers, while reducing the amount of energy not supplied by reducing the lost client minutes (CML). Direct vectors $g_y > 0$ means the expansion of the desired output, while the $g_b > 0$ means shortening the unwanted exit. The relationship between the directional distance function and the revenue function reveals the shadow price of unwanted outputs [20]. Let p indicate good production prices, and q indicates poor product prices. They are presented as:

$$p = (p_1, \ldots, p_M) \in R_+^{\ M} \tag{3.33}$$

$$q = (q_1, \ldots, q_J) \in R_+^{\ J} \tag{3.34}$$

Then the revenue function is introduced to account for negative income generated by bad results. Negative income due to unwanted output (CML) is defined by the income function as:

$$R(x, p, q) = max_{yb}\{py - qb : (y, b) \in P(x)\} \tag{3.35}$$

The revenue function, R (x, p, q), gives the largest possible income that can be obtained from input data, x, when the production technology, electricity in our case, has good prices for production, p, and poor prices for products, q. Desired output prices (p) and unwanted release prices (q) can be used to calculate the largest possible revenue in terms of the directional distance function D_0 as:

$$R(x,p,q) \geq (py-qb) + p\vec{D}_0(x,y,b;g)\cdot g_y + q\vec{D}_0(x,y,b;g)g_b \tag{3.36}$$

The left side of the equation means the maximum income, while the right side is equal to the actual income (py − qb) plus the profit from generating income from the elimination of technical inefficiency. The increase in revenue from the elimination of technical inefficiency has two components: (3.27) profit by increasing good outputs ($pD_0(x, y, b; g)\cdot g_y$) and (3.28) increase by reducing poor results ($qD_0(x, y, b; g)\cdot g_b$) - since the cost of bad outputs is deducted from good incomes. The permutation (3.36), the directional output distance function, and the maximum revenue function are related to:

$$\vec{D}_0(x,y,b;g) \leq \frac{R(x,y,q)-(py-qb)}{pg_y+qg_b} \tag{3.37}$$

The directional output distance function given in equation (3.31) can also be recovered from the revenue function as:

$$\vec{D}_0(x,y,b;g) = \min_{p,q}\{\frac{R(x,y,q)-(py-qb)}{pg_y+qg_b}\} \tag{3.38}$$

Applying the envelope theorem twice to (3.38) gives our shadow price model:

$$\nabla y\vec{D}_0(x,y,b;g) = \frac{-p}{pg_y+qg_b} \tag{3.39}$$

$$\nabla y\vec{D}_0(x,y,b;g) = \frac{q}{pg_y+qg_b} \tag{3.40}$$

Details of the physical significance of the shadow pricing technique are explained in detail in the link [20]. If we assume that we know m-n in the price of a good release (in our case, the operating costs of the DSO), then the j-a nominal bad release price (the price of one minute of interruption) can be calculated as [22]:

$$q_j = -p_m\left(\frac{\dfrac{\partial \vec{D}_0(x, y, b; g)}{\partial b_j}}{\dfrac{\partial \vec{D}_0(x, y, b; g)}{\partial y_m}}\right) \tag{3.41}$$

References [23,24] parametrize the function of directional distance using a quadratic function. Now we must choose our directional vector g so that we can increase the amount of energy provided to customers and reduce customer disruptions for the year. 1, 0 and −1 within the vector g means an increase, no change and decrease in outputs, respectively. For example, g = (1, 0) means expanding the desired outputs, while keeping unwanted outputs the same. Since our goal is to simultaneously increase good outputs and reduce bad outputs, the directed vector g = (1, 1) is set. We assume that there are k = 1,... , K DSOs, then the quadratic distance function for k-th DSO is shown in the equation (3.42): where, l: the constant of the quadratic distance function for the k-th DSO is shown in the equation (3.42):

where,

l: quadratic function constant of directional distance,

α_n: input coefficients,

β_m: desired exit coefficients,

γ_j : unwanted exit coefficients,

α_{mn}': quadratic input coefficients,

β_{mm}': square of the desired output coefficients,

$\gamma_{jj'}$: quadratic unwanted output coefficients,

δ_{nm}: product of inputs and desired output coefficients,

η_{nj}: product of inputs and coefficients of undesirable outputs,

μ_{mj}: product coefficients of desired and unwanted outputs.

Parameters (3.42), l, α_{n}, α_{mn0}, β_{m}, β_{mm0}, γ_{j}, γ_{jj0}, δ_{nm}, η_{nj}, μ_{mj} , are selected to minimize the amount of deviations of the value of the function of the directional distance from the border technology (in our case, electricity supply). The coefficients of equation (3.42) are calculated by solving equation (3.43), taking the directed vector as g = (1, 1). Equation (3.44) requires that the I / O vector be feasible. Equations (3.45) and (3.46) impose monotonic conditions of equations (3.39) and (3.40). Equation (3.47) imposes positive uniformity on the inputs for the average level of input use. That is, at the average level of inputs, $\bar{x}$, increasing the input usage, which keeps the good and bad outputs constant, leads to an increase in the function of the distance of the directional output, which means greater inefficiency. Equation (3.48) is related to the translation property of equation (3.32).

$$\begin{aligned}
&\overrightarrow{D}_0 = (x_k, y_k, b_k; 1,1) \\
&= l + \sum_{n=1}^{N} \alpha_n x_{nk} + \sum_{m=1}^{M} \beta_m y_{mk} + \sum_{J=1}^{J} \gamma_j b_{jk} + \frac{1}{2} \sum_{n=1}^{N} \sum_{n'=1}^{N} \alpha_{mn'} x_{nk} x_{n'k} \\
&+ \frac{1}{2} \sum_{m=1}^{M} \sum_{m'=1}^{M} \beta_{mm'} y_{mk} y_{m'k} + \frac{1}{2} \sum_{m=1}^{M} \sum_{m'=1}^{M} \beta_{mm'} y_{mk} y_{m'k} + \frac{1}{2} \sum_{j=1}^{J} \sum_{j'=1}^{J} \gamma_{jj'} b_{jk} b_{j'k} \\
&+ \frac{1}{2} \sum_{n=1}^{N} \sum_{m=1}^{M} \delta_{nm} x_{nk} y_{mk} + \frac{1}{2} \sum_{n=1}^{N} \sum_{j=1}^{J} \eta_{nj} x_{nk} b_{jk} + \frac{1}{2} \sum_{m=1}^{M} \sum_{j=1}^{J} \mu_{mj} y_{mk} y_{jk}
\end{aligned} \tag{3.42}$$

Then an optimization model is established that minimizes the number of deviations of the value of the directed distance function from the border technology (in our case, electricity supply), see from Equations (3.43) -(3.49). And the variable solutions in the optimization model are l, α_{n}, α_{mn0}, β_m, $\beta_{mm'}$, γ_j, $\gamma_{jj'}$, δ_{nm}, η_{nj}, μ_{mjj} and were solved using Python.

$$Minimization \sum_{k=1}^{K} [\overrightarrow{D}_0(x_k, y_k, b_k; 1,1) - 0] \tag{3.43}$$

$$\overrightarrow{D}_0(x_k, y_k, b_k; 1,1) \geq 0, \;\; k = 1, \ldots, K \tag{3.44}$$

$$\frac{\partial \overrightarrow{D}_0 = (x_k, y_k, b_k; 1,1)}{\partial b_j} \geq 0, \;\; j = 1, \ldots, J; \;\; k = 1, \ldots, K \tag{3.45}$$

$$\frac{\partial \overrightarrow{D}_0 = (x_k, y_k, b_k; 1,1)}{\partial y_m} \leq 0, \; m = 1, ..., M; \; k = 1, ..., K \tag{3.46}$$

$$\frac{\partial \overrightarrow{D}_0 = (\overline{x}_k, y_k, b_k; 1,1)}{\partial x_n} \geq 0, \; n = 1, ..., N; \tag{3.47}$$

$$\sum_{m=1}^{M} \beta_m + \sum_{J=1}^{J} \gamma_j = -1; \; \sum_{m'=1}^{M} \beta_{mm'} - \sum_{j=1}^{J} \mu_{mj} = 0, \; m = 1, ..., M; \tag{3.48}$$

$$\sum_{j'=1}^{J} \gamma_{jj'} - \sum_{m=1}^{M} \mu_{mj} = 0, \quad j = 1, ..., J; \; \sum_{m=1}^{M} \delta_{nm} - \sum_{j=1}^{J} \eta_{nj} = 0, \; n = 1, ..., N$$
$$\alpha nn' = an'n, \; n \neq n'; \; \beta_{mm}{}' = \beta_{m'm}, \; m \neq m'; \; \gamma_{j'j} = \gamma_{jj'}, \; j \neq \vec{j} \tag{3.49}$$

Conclusions to the third section

Methods of forming a system of tariffs to overcome the power shortage in the power system are considered. It is established that a few methods can be used for the UES of Ukraine in modern market conditions.

Each of the considered methods needs additional elaboration considering the establishment of its capabilities in the current events in the electricity markets and consumer participation in these markets. Because the main issue of this process is the need to develop different versions of the methodology, the formation of tariffs to make the consumer feel a full participant in the process and enter the electricity market to reduce power shortages.

SECTION 4

Application of methods of consumer participation in reducing the power deficit of the power system

4.1 Analysis of statistical data for the formation of assessment indicators

From the subjects of state influence, based on statistical data, indicators for assessing the reliability of electricity supply are formed, it is important to consider: the State Inspectorate of Energy Supervision of Ukraine, which performs control functions; NEURC of Ukraine, which performs the functions of regulation.

The State Inspectorate for Energy Supervision of Ukraine, according to [25], carries out state energy supervision of electrical installations and networks of market participants. The Office monitors compliance by market participants (excluding consumers) with the requirements of rules and other regulations and regulations on the technical operation of power plants and networks, the technical condition of electrical installations and networks.

NEURC of Ukraine is a permanent central executive body with a special status [26]. The regulator carries out state regulation to achieve a balance of interests of consumers, businesses operating in the fields of energy and utilities, and the state, energy security, European integration of electricity and natural gas markets of Ukraine. In accordance with its powers: sets tariffs for electricity distribution services and economic coefficients of regulatory technological costs of electricity in electricity networks; monitors the implementation of the DSO requirements for non-discriminatory access to electricity networks, considers complaints of users of the distribution system and resolves disputes; controls the quality of services.

For settlements for the formation of tariffs for interruption of power supply requires several indicators for the settlement year, such as: the number of concluded contracts of subscribers for the provision of distribution services, the volume of electricity distribution, MWh, operating costs for the maintenance of the power system, the economic condition of the equipment of electrical networks, the indicators of SAIDI and SAIFI.

Information on the number of concluded consumer agreements on the provision of distribution services for 2020-2021 is shown in Figure 4.1

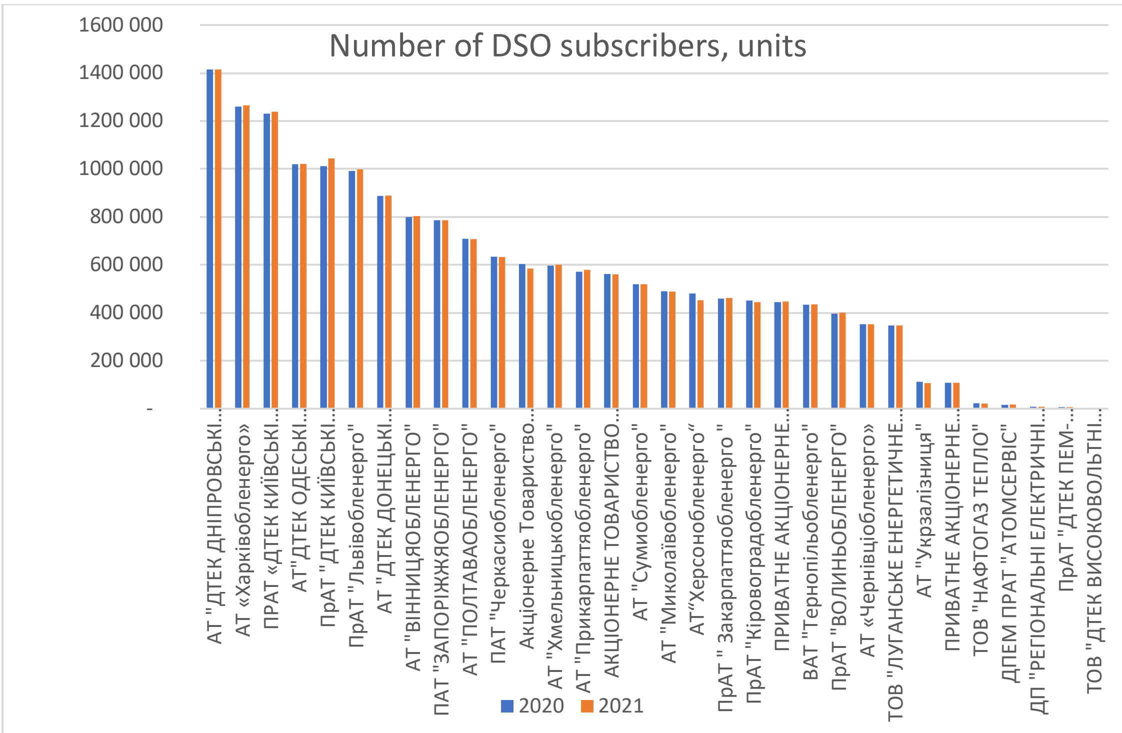


Figure 4.1 Number of concluded contracts of subscribers for the provision of distribution services for 2020-2021[2]

The growth in the number of subscribers over the years for each DSO was within 0.01%.

So, we can conclude that there is no rapid increase in the number of DSO subscribers over the years, and these data can be considered relevant for calculations.

The following indicator for calculations is the volume of electricity distribution, MWh is shown in Figure 4.2

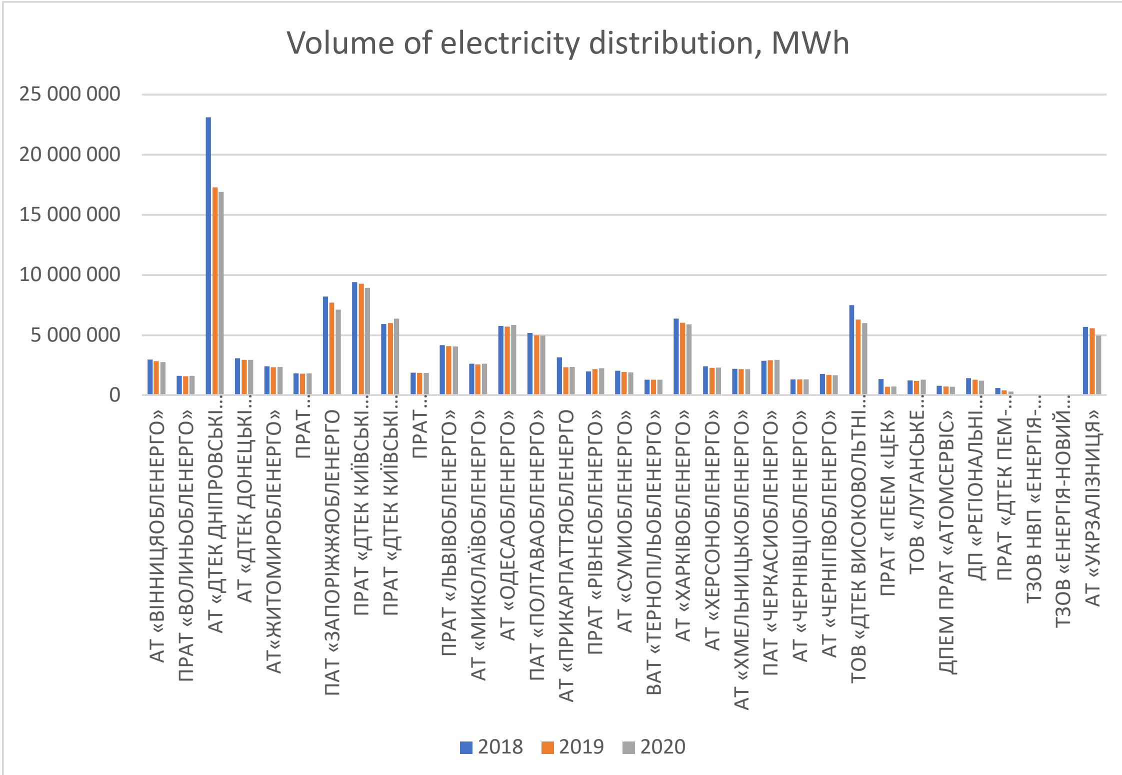


Figure 4.1.2 volume of electricity distribution for 2018-2020, MWh [2].

In total, the volume of electricity distribution for 2018-2020 was stable at the same level, except for DTEK High Voltage Networks LLC due to the reduction in production at the Nikopol Ferroalloy Plant.

The next indicator necessary for calculations are operating costs. This indicator for 2019-2020 was calculated due to the indicators of the volume of electricity distribution and the tariff rate. Estimated operating costs for 2019-2020 are shown in Figure 4.3

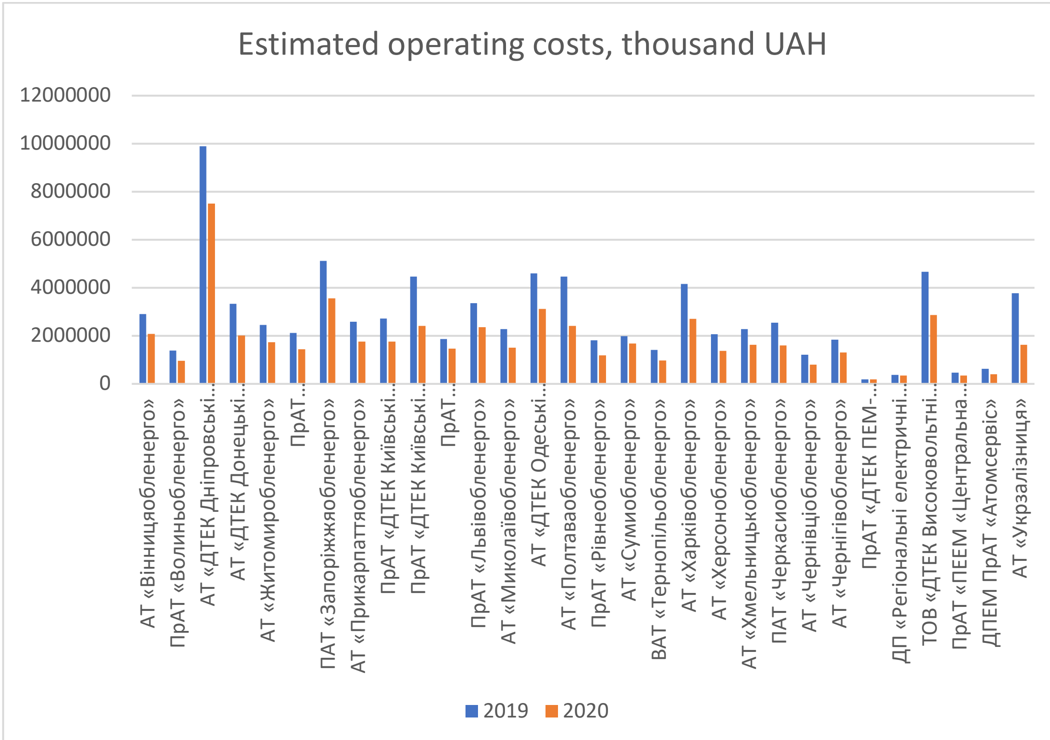


Figure 4.3 Estimated operating costs for 2019-2020

As can be seen from the graph, the increase in operating costs in 2020 compared to 2019 is associated with several indicators of the main of which the electricity tariff, which increased by an average of 52% in 2020.

The next indicator is the technical condition of the equipment of electrical networks, namely, the percentage of all networks for each of the DSO that require current or major repairs. Figure 4.4 shows the technical condition of the equipment of electrical networks.

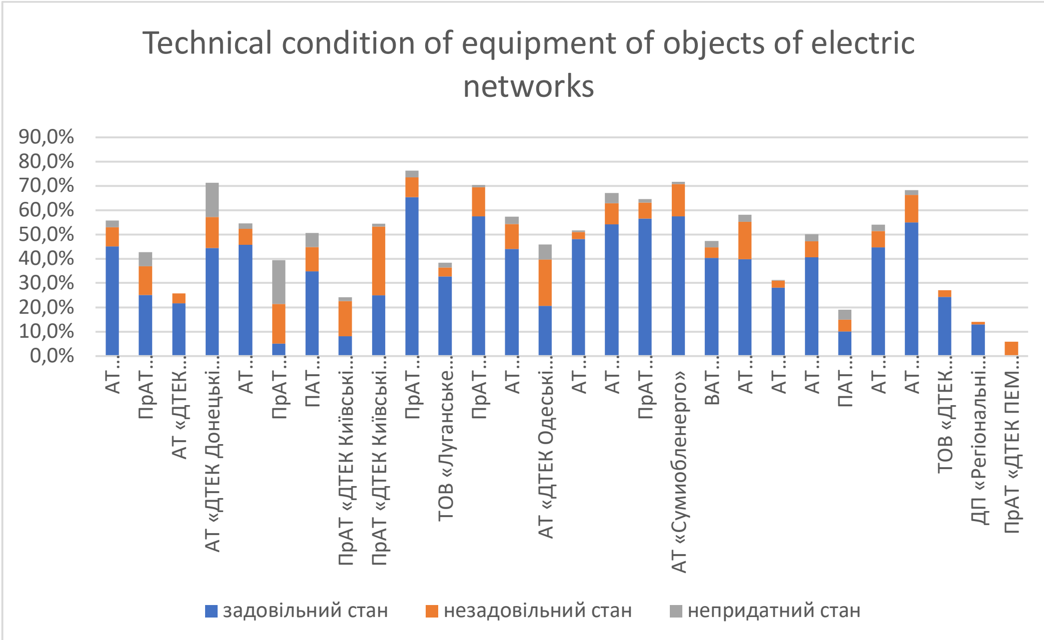


Figure 4.1.4 Technical condition of equipment of electrical networks

As can be seen from this graph, a large percentage of equipment for all DSOs needs repair or replacement, which causes high operating costs, since part of the electricity tariff is the depreciation costs of equipment.

Another important indicator for calculations is SAIDI indicator.

The dynamics of SAIDI and ENS indicators for 2012 – 2019 (through the fault of companies) was given in the first section in Figure 1. 3. And the actual values of the indices of the average duration of long power interruptions in the system (SAIDI) at voltage levels of 0.4–110 kV for 2018 – 2019, min. are shown in Figure 4.5.

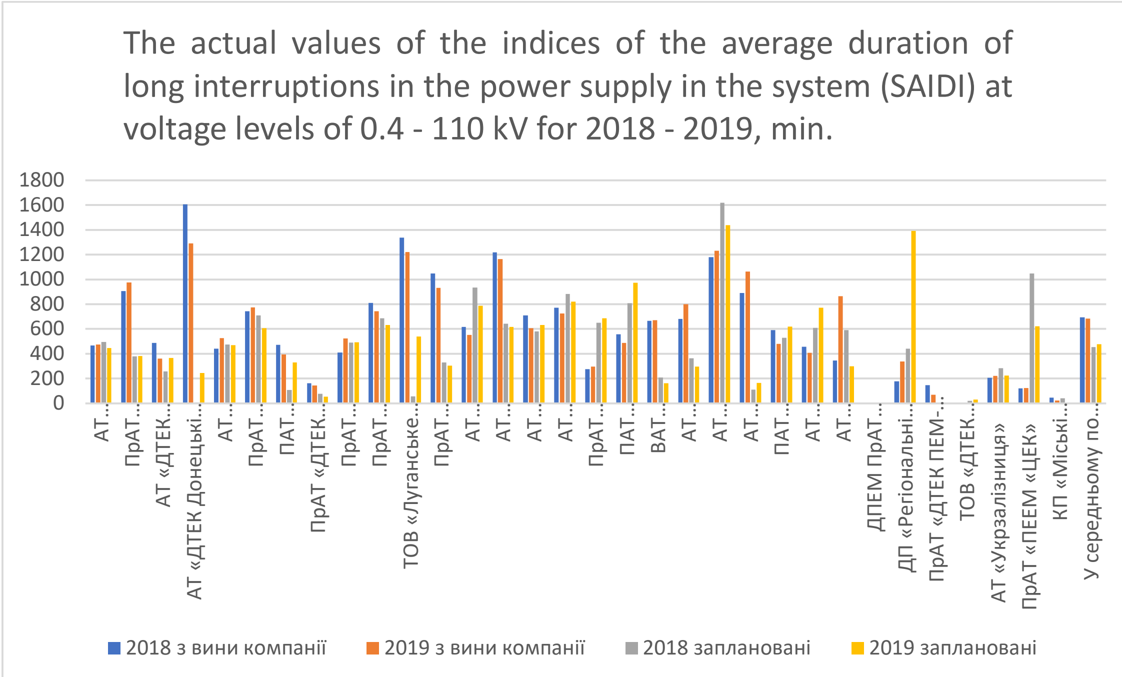


Figure 4.5 Actual values of the indices of the average duration of long power interruptions in the system (SAIDI) at voltage levels of 0.4 – 110 kV for 2018 – 2019, min.

The graph shows that SAIDI indicators in Ukraine are much higher than in Europe, this is due to the technical condition of electrical networks, many of which need to be updated.

4.2 Calculation of the cost of consumer participation in reducing the power deficit

The methodology given in the third section to determine the discount on consumer participation in reducing the electricity shortage of the power system can be illustrated by an example of setting a discount for wholesale electricity consumers (Oblenergos, independent electricity suppliers).

The discount on the participation of wholesale consumers in reducing the electricity shortage of the power system can be determined based on indicators of reliability of the generating part of the power system, forecast graphs of the electrical load of the united power system of Ukraine, modeling of capacity demand coverage.

4.2.1 Determination of reliability indicators of the generating part of the electricity system

The initial values for determining the probability of finding power system generators in a certain state (working - non-working) are the maximum operating capacities and coefficients of widespread use of power units with a capacity of 150 - 800 thousand kW for 2021.

In this example, the task of constructing a model of possible states of the generating part of the power system is performed by equivalence methods, since this allows you to significantly simplify and speed up the solution of the problem.

We determine the value of the coefficients of widespread use of the equivalent unit and forced downtime according to the formulas (3.7) and (3.8):

$$K_F^E = 52{,}29\% \text{ and } K_R^{Э} = 47{,}71\%$$

According to the recommendations [27], the number of equivalent units is assumed to be equal to the actual number of power units that were in operation at thermal power plants in Ukraine in 2022, i.e., $\boldsymbol{n^e = 75}$, and the maximum operating power of one equivalent block is determined by the formula (3.10):

$$P^E = \frac{21842}{75} = 291{,}226 \text{ thousand kW}$$

When building a model of the space of possible states of the power system, we believe that each individual equivalent power unit can be in one of two states - working and non-working (the unit is disconnected). The desired model is built by listing the possible states of the power system, that is, by alternately "disconnecting" one or more equivalent power units.

When building a model of the space of possible states of the power system, we believe that each individual equivalent power unit can be in one of two states - working and non-working (the unit is disconnected). The desired model is built by listing the possible states of the power system, that is, by alternately "disconnecting" one or more equivalent power units as:

$$C_{75}^{1} = \frac{75!}{1!\cdot(75-1)!} = 1$$

$$B_{1} = 1 \cdot 0,4771^{1} \cdot 0,5229^{74} = 1,32^{-28}$$

The construction of this model of the state space of the power system was carried out using a PC. The results of the calculation of the possible states of the power system are presented in table C.2. The graph "system state" shows the rounded values of the total power of the operating generators of the power system, and the graph "probability of the state of the system" shows the general probabilities of finding the energy system in each of the possible states.

4.2.2 Modeling of coverage of the total electrical load of the power system

The initial data for the construction of the load coverage model, as already noted, are the hourly values of electricity consumption in the united power system of Ukraine, projected on the characteristic days of each month of the planned year minus the load of indoor nuclear power plants and hydroelectric power plants. The actual load schedule for 2021 covered by the TPP was adopted as a projected load schedule.

The projected hourly values of the power system load are ranked in descending order, i.e. we make an ordered load schedule. The same hourly load values are combined according to the formula (3,12) of this procedure. Ranking of the forecasted hourly values of loading is carried out by means of the personal computer. The results of drawing up an orderly schedule of power system load are shown in Fig. 4.6

4.2.3 Determination of the expected lack of electricity supply in the power system and the average electricity shortage

For each state of the power system (Table. C.2), based on an orderly schedule of projected hourly load values (Fig. 4.6), determine the time during which the projected load of the power system will exceed the total operating capacity of power plants.

For example, the state of the power system with a total capacity of generators of 21,842 thousand kW (Table. C.2) corresponds to a time of 1562,188 hours. Further determination of indicators of reliability of the power system is carried out according to the formulas (4.13 - 4.17) of this technique using a PC.

Figure 4.6 TPP load coverage schedule

The probability of loss of load probability (LOLP) or the probability of system failure is:

$$\boldsymbol{LOLP} = 65.57\ \%.$$

At the same time, the probability of loss of load on the power system, expressed in hours per year, is:

$$\boldsymbol{LOLP_o} = 5743{,}93 \text{ hours/year}.$$

As a result of the calculation, the total expected undersupply of electricity to consumers during the year is determined as the sum of the undersupply of electricity for all states and is:

$$\boldsymbol{E} = 46576389{,}56 \text{ kWh}$$

Thus, the average deficit of electrical power of the power system is:

$$P_{av.\partial} = \frac{146576389{,}56}{5743{,}93} = 8108{,}801 \text{ MW}$$

4.2.4 Justification of the level of discount for participation in reducing the power deficit of the power system.

The task of reducing the power deficit of the energy system at the level of the Energy Market can be solved by one of the options proposed above. To date, the most preferable option is the second option, in which consumers, for the provided discount on payment for electrical energy, agree to limit their power and transfer consumption from peak hours to hours of failure of the power system load.

As already noted, the determining factor in the proposed approach is the determination of the block fee for being in a hot spare. Currently, there are 75 units in the power system with an installed capacity of 150 to 800 thousand kW. Considering the fact that at the calculation stage it is not possible to establish which of the blocks and for what period of time will be idle, it is most advisable to operate in this case with specific weighted average costs for maintaining the unit at idle.

The average values of idle costs for power units of various capacities, determined by the price applications of thermal power plants, are given in table 4.1.

Using the data given in table 4.1, we determine the specific weighted average value of the costs for idling:

$$\overline{Z}_{hr}^{aw} = 34,55 \text{ UAH/(thousand kWh)}$$

Table 4.1 Average value of idling costs for power units of TPPs of Ukraine

№ п/п	Installed capacity of the unit	Number of units in the power system	Average idling costs, thousand UAH/hour
1	150	6	4,628
2	175	22	7,2
3	195	10	5,85
4	200	7	6,96
5	275	9	7,68
6	282	7	9,4
7	285	3	8,88
8	300	23	10,153
9	800	6	26,712

Having specific weighted average value of the costs for idling and consistent power P_{agreed} = 1760 thousand kW we can determine the average total cost of blocks at idle при: $\overline{Z}_{hr} = 60808$ UAH/h. Then, the annual fee to the blocks for being in the hot reserve is determined by the formula (3.19):

$$\Delta D_{hr} = 60808 \cdot 8760 = 532,678 \cdot 10^6 UAH$$

Considering the existing probability of loss of load by the power system, an appropriate reserve of generating capacities should be created to ensure reliable and trouble-free operation, or it should be possible to reduce the burden of consumers by the amount $P_{aw.s}$ in the event of a power shortage. According to [31] in the power system, a power reserve of 600 thousand kW should be maintained. Thus, the calculated value of the power deficit of the power system of 8108.801 thousand kW should be reduced by 600 thousand kW and equal to 7508.801 thousand kW.

We assume that part of the expected average annual shortage of electrical power is covered by the agreed limitation of the consumed load of ten wholesale consumers of electrical energy (DSO) Table 4.2.

In this example, the average residence time of the required piece of equipment in the hot standby is taken to be equal to the duration of the hours of the maximum load of the power system during the year:

$$T^{PM} = 6 \cdot 365 = 2190 \text{ ч / год}$$

Then the amount of electrical power that will not be consumed during the hours of maximum loads of the power system, by consumers who have agreed to limit the electrical capacity, during the year will be according to the formula (4.25):

$$E_{agreed} = 1760 \cdot 2190 = 3854,4 \cdot 10^6 kWh$$

Table 2 Energy supplying organizations involved in reducing the capacity deficit of the energy system of Ukraine

№	Energy supply organization	Average daily power consumption, MW	Agreed limit of electrical power, MW
1	PJSC "DTEK KYIV REGIONAL GRIDS"	450.0867	50
2	JSC "DTEK DNIPRO GRIDS"	3040.572	500
3	PJSC "ZAPORIZHZHYAOBLENERGO"	1296.236	100
4	PJSC "DTEK KYIV GRIDS"	745.4281	50
5	JSC "PRYKARPATTYAOBLENERGO"	305.0718	50
6	JSC "DTEK ODESA GRIDS"	523.3458	50
7	JSC "POLTAVAOBLENERGO"	562.3994	50
8	JSC "KHARKIVOBLENERGO"	823.9078	50

Based on statistical data, the price DAM is determined, as well as the price IDM for each hour of the day. As can be seen from table C.3, the upper limit weighted average wholesale price of electricity fixed on the level 3746,549 UAH/MWh

Thus, according to Table. C.3, the average wholesale price of a power system is as follows: $C_{aw}^{wh} = 2591,308 UAH / MWh$, and the average purchase price of electricity for the time of load failure according to the formula (3.24) is: $C_{aw}^{l.f.} = 1039,82 UAH / MWh$

Then, the annual savings of the Energy Market with the agreed load limit are determined according to the formula (3.21):

$$\Delta D_E = (2591,308 - 1039,82) \cdot 3854,4 \cdot 10^6 = 5980 \cdot 10^6 UAH.$$

Thus, the expected annual savings of the Energy Market are determined by the formula (4.18):

$$\Delta D_e = (532,678 + 5980) \cdot 10^6 = 6512.678 \cdot 10^6 UAH$$

The share of total annual cost savings of the electricity energy market related to each of the electricity supply companies involved in reducing the power deficit in the power system is determined in proportion to the value of the agreed limitation of their electrical load and is determined according to the formula (4.26) for "Kharkivoblenergo":

$$\Delta D_1 = \frac{6512.678 \cdot 10^6}{1760} \cdot 50 = 1850.19 \cdot 10^6 UAH$$

Similar calculations are performed for all remaining energy supply organizations that have agreed to limit their electrical load in the event of a power deficit in the power system. The results of calculating the discount for energy supply organizations are shown in Fig. 4.7.

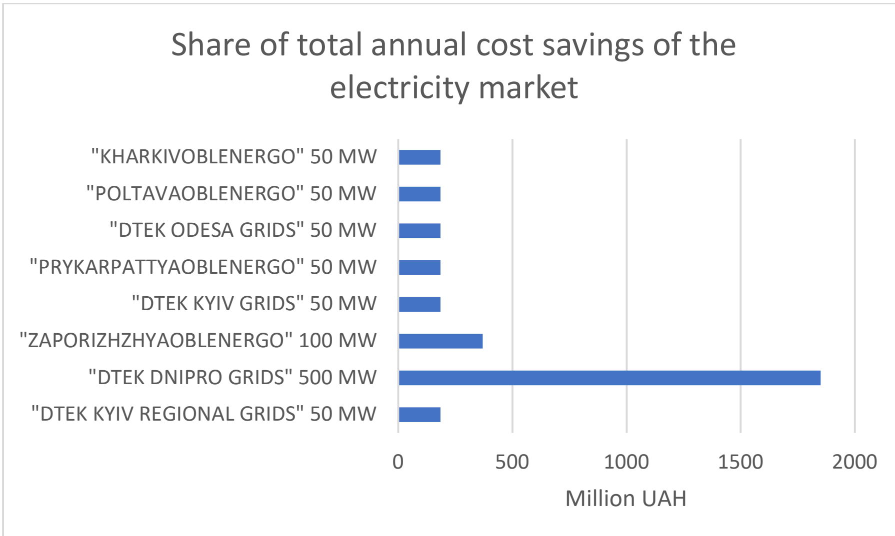


Fig.4.7 Share of total annual cost savings of the electricity market

Thus, the specified ten wholesale consumers of electricity (DSO) should be provided with an annual discount on the purchase of electricity in the Energy Market of Ukraine.

The discount received by wholesale consumers on payment for electricity, according to the above methodology, can be distributed within each wholesale consumer (DSO) among its retail consumers, directly providing an agreed amount of reduction in electrical capacity.

4.3 Determination of the shadow price for interruption of power supply for Finland

Empirical study [28] explores Finland. Even though Finland has a reliable electricity infrastructure, security of supply is at risk of extreme weather events. These events can lead to long-term outages, which could eventually force Finnish DSOs to invest and spend more money on operating and operating costs. The study used data from 78 Finnish DSOs for 2013, 2014 and 2015. To investigate the directional distance function, the Finnish Energy Market Authority (Energiavirasto) selected data on the energy provided, the number of customers, the share of underground cables, operating costs and the average system interruption duration index (SAIDI) for each DSO SAIDI calculated as:

$$SAIDI = \frac{\text{the sum of all customer outages for the year}}{\text{total number of clients served}} (h.) \tag{4.1}$$

The amount of all customer breaks per year can also be determined in terms of lost customer minutes (CML) per year. Therefore, the CML is calculated as:

$$CML = SAIDI \cdot 60 \ \cdot \text{number of clients} \left(\min.\right) \tag{4.2}$$

The proportion of underground cables in distribution lines (SC in%) and operating costs (OPEX in euros) were chosen as inputs, while energy supplied to low voltage customers (ES in GWh) and lost customer minutes (CML in minutes) were identified as desirable and undesirable outputs respectively. Descriptive statistics of input and output variables are shown in Table 4. 3 by specifying the average, standard deviation, minimum and maximum values of each dataset from 2013, 2014 and 2015 for 78 Finnish DSOs. A total of 936 sample observations were used in the analysis. OPEX and CML are presented in thousands of euros and thousands of minutes, respectively. In addition, the supplied energy is transferred to GWh.

Table 4.3 Descriptive Statistics for Combined Sample Observations, 2013–2015.

	Inputs		Desirable Output	Undesirable Output
	SC (%)	OPEX (k €)	ES (GWh)	CML (k mins)
2013				
Mean	47.27	3015.51	619.92	14,299.67
Stdev.	25.60	5674.63	1200.07	45,908.75
Minimum	3.04	35.35	16.67	0.81
Maximum	100.00	32,156.33	7492.00	300,711.21
2014				
Mean	48.65	2891.61	616.07	5367.14
Stdev.	25.46	5021.57	1189.88	14,184.51
Minimum	3.23	55.30	16.38	1.90
Maximum	100.00	25,616.35	7425.00	85,712.50
2015				
Mean	50.34	3134.97	613.64	14,575.97
Stdev.	25.27	5857.64	1177.45	56,013.63
Minimum	3.30	71.00	15.84	6.18
Maximum	100.00	29,906.08	7283.00	448,823.76

Within the framework of this optimization model, the objective function of the equation (3.43) was solved using the limitations of equations (3.44) -(3.49) in the Python programming language in order to optimize the problem, and the following coefficients were calculated and presented in Table 4. 4. When linear programming variables are assigned, a free form of "Continuous" was chosen to get a relaxed solution. A number of the 1,176 constraint equations were created with the script using equations (3.44) -(3.49), and they were added to the task to find the optimal solution.

After calculating the coefficients, the equation (3.41) is solved where p is accepted as 5.5 euro cents as the average price of electricity distribution in Finland [29], and the results are summarized in table B1 in Annex B.

Table 4.4 Coefficients of equation (3.42) per year.

Variables	2013	2014	2015
l	16.3252	0.007764978	0.017882857
α_1	0	0	0
α_2	-7×10^{-10}	0.24284221	0.27902876
β_1	-1	-0.99987881	-1
γ_1	0	0.000121188	0
α_{11}	0	0	0
α_{22}	-1×10^{-10}	0.050119522	0.020527845
β_{11}	0	-1.977×10^{-7}	0
γ_{11}	0	-1.977×10^{-7}	0
α_{12}	0	0	0
δ_{11}	0	0	0
δ_{21}	0	0.000204027	0
η_{11}	0	0	0
η_{21}	0	0.000204027	0
μ_{11}	0	-1.977×10^{-7}	0

The shadow price for each DSO means the price of one minute of interruption in terms of operating costs. The main goal is to increase the desired output by one unit while reducing the unwanted output by one unit. The shadow price of power outages in 2015 is shown in Figure B1 in Annex B. After the analysis, it is clear that the shadow prices of a one-minute shutdown for most DSOs vary between 0.4-0.5 euro cents during 2013-2015. It should be noted that as the CML gradually decreases, the shadow price will increase. Therefore, the results of this analysis give the lowest costs incurred due to interruptions.

In addition, shadow prices are determined by the directional *vector g*. Vector shows a gradual expansion or reduction of outputs.

In this analysis, only *g* (1, 1) were used, however, the directed vectors *g* (1, 0) and *g* (0, −1) can be used.

In Finland, DSO is required by law to pay certain compensations to customers, which vary depending on the annual interrupt time of customers. According to this legislation, in the case of one outage exceeding the permissible limit, the operator must pay the corresponding percentage of the annual fee for delivering electricity back to the customer. The maximum amount of compensation to be paid to one client is limited to

EUR 1,200/year. Table 4. 5 summarizes the standard customer compensation scheme used in Finland.

Table 4.5 Standard compensation to customers in accordance with legislation adopted during 2013.

Standard Customer Compensation	
Outage Duration (h)	Compensation (%)
12–24	10
24–72	25
72–120	50
120–192	100
192–288	150
>288	200

Theoretically, the amount of compensation should not be lower than bad income (in this case, the cost of power outages), calculated by the shadow price of the unwanted release multiplied by the unwanted output (CML), as in equation (4.3).

$$R = qb \tag{4.3}$$

To offer a simpler comparison between shadow pricing power outages and standard compensation, let's define the price of compensation as follows:

$$compression = \frac{\text{Standard compensation paid to DSO}}{CML} \tag{4.4}$$

The cost of compensation is calculated in euros, for a lost minute, as a break. The results for 2015 are summarized in Figure 2 in Annex B , it is clear that the majority of Finnish DSO did not pay any compensation at all during 2015, according to the legislation in table 4.5. Most compensation prices range from 0.1 €cent/ outage minutes to 1€cent/ outage minutes, while for Rantakairan Sähkö Oy the compensation price exceeds 5€cents.

Finally, to see the results better, the comparison between shadow prices and compensation prices for finnish DSO for 2015 is shown in Figure 4.7.

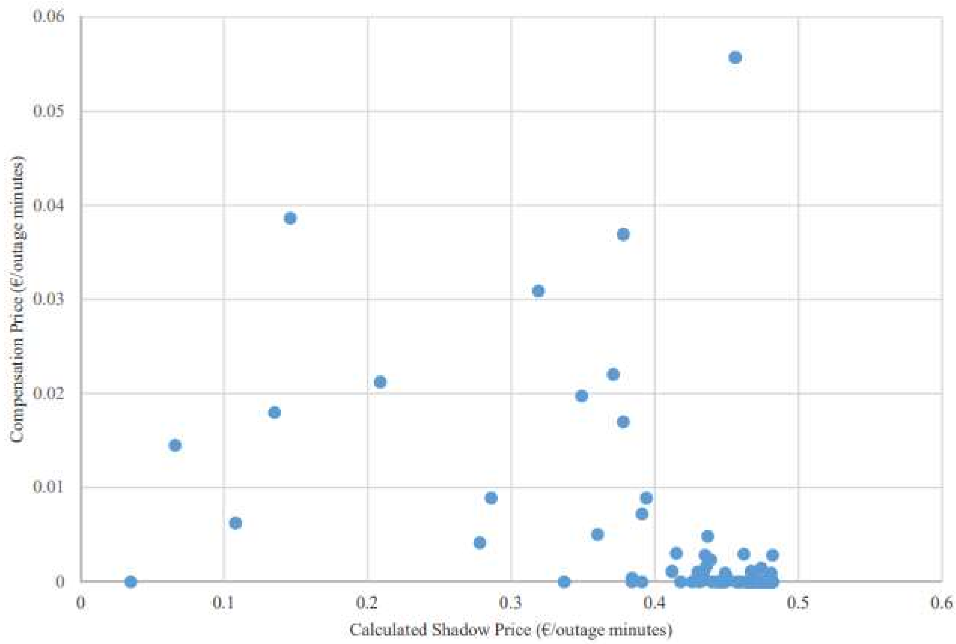


Figure 4.7 Compensation price of one minute break during 2015 (euro cents)

Figure 4.7 shows that among the 78 Finnish DSO, only 35 paid compensations during 2015.

In the article [20] the authors present a method of shadow pricing of power outages, which is based solely on publicly available analytical data, and not on survey questionnaires.

This cost estimate can only be done using publicly available and objective analytical data such as the number of customers, the share of cables in the distribution system, the energy supplied to low voltage customers and SAIDI. However, the main advantage of achieving specific customer outcomes using the customer survey methodology does not apply here. Shadow pricing technique gives average results, which omits industry differences in electricity consumption and customer interruption costs. It should be remembered that the cost of a one-minute break for a residential consumer and the same cost for an industry customer will be different. In addition, this cost will vary significantly among subsectors with the same sector, for example, in the textile, construction, chemical and pharmaceutical industries.

To achieve a specific estimate of customer outage costs, network operators must share industry-specific and specific energy consumption data with specific customers.

In the study [20] Analytical data shared by 78 Finnish DSO operators, which provide 99% of the energy for low voltage customers in Finland, was used. This article assesses the problem from the point of view of the DSO, so that each DSO has more information about interruption losses quickly and simply. In some countries, such as the United Kingdom and Finland, customers are protected by laws that require DSO to pay certain compensation in the event of a break. In Finland, the electricity law states that if a single interruption event is between 12 and 24 hours, the DSO must pay 10% of the annual fee for the delivery of electricity back to the customer.

Based on these observations, it can be concluded that in Finland, although some of the DSO did not offer sufficient compensation for power outages, some DSO overcompensated for power outages. Price signals are crucial in terms of ensuring continuous service quality and future investment.

4.4 Determination of the shadow price for interruption of power supply for Ukraine

To carry out such calculations for the DSO of Ukraine, it is necessary to consider that Finland has much lower indicators given in subsection 4.3 relative to the indicators of Ukraine given in subsection 4.1. Therefore, I consider it advisable to carry out similar calculations within the framework of one DSO, the indicators of which will not be much divergent in values from Finland’s indicators.

Kharkivoblenergo, DTEK Odessa Electric Networks, and DTEK Kyiv Regional Electric Networks PJSC were selected for the calculations. After calculations, similar to those presented in 4.3, the shadow price for power outages was calculated. The shadow price for power outages in the Ukrainian DSO is given in Table 4.6

Table 4.6 Shadow price for interruption of power supply to Ukrainian DSO

	Shadow price UAH/min	Shadow price € cents /min
"Kharkivoblenergo"	1,21	0,039
"DTEK Odesa Grids"	1,28	0,041
"DTEK Kyiv Regional Grids"	1,08	0,035
Finland's DSO average	1,24	0,04

Based on these observations, we can conclude that if we improve the legislative framework and establish contact of the DSO with consumers, then such interruption prices will be of interest to consumers in balancing the power system. Price signals are crucial in terms of ensuring continuous quality of service and making future investments.

This information is necessary for the future planning of power systems, strengthening of existing infrastructure, as well as for the purposes of paying standard compensation.

Conclusions to the fourth section

In this section, an analysis of statistical data that are required for further calculations was carried out. A calculation was made on two methods.

It was found that although these methods are similar in purpose, the impact of each method on the interest of the consumer in reducing the power deficit is different. And the fundamental question is that each of these methods in its methodological essence can be tied to the modern model of the energy market.

It was also found that the methodologies under consideration are now not adapted to modern legislation, and it requires revision and adaptation to modern approaches to price formation in our electricity markets.

CONCLUSION

1. The issue of reliability, security of supply is one of the important and long-standing tasks for the UES of Ukraine, as evidenced by a significant number of interruptions in electricity supply and a significant shortage of electricity to consumers.

2. The only but quite complex and destructive is the use of automated frequency unloading systems in the power system, which implement the tasks of limiting electricity consumption. But in market conditions, the use of such systems should be reduced, maximizing the use of economic methods to manage demand.

3. The modern model of the energy market has certain shortcomings, in particular in terms of the formation of insufficient consumer interest in participating in the management of its electricity consumption and to involve it in reducing power shortages in the power system. This is due to the low level of market integration, a significant mismatch between the price offered in the market, with the real losses borne by the consumer in terms of management.

4. The considered methods provide an opportunity to implement the task of electricity consumption management, consumer involvement in the process of reducing power shortages in the power system, but they need to adapt to the modern system of relations in the electricity market.

5. Implemented adaptation of methods proved their practical value, the possibility of using the results to further expand market relations in energy markets, expand the ability of each of the markets to implement management tasks in the energy system.5. Implemented adaptation of methods proved their practical value, the possibility of using the results to further expand market relations in energy markets, expanding the ability of each market to implement management tasks in the energy system.

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ANNEXES

Annex A

Instructions for investigation for 2020 in the work of energy enterprises of Ukraine, which are supervised by the Department of State Supervision over the operation of electrical stations and networks, there were 461 technological violations classified as failures of 1 and 2 categories, compared to 409 technological violations for the same period of 2019 (an increase of 52) namely:

JSC "DTEK Dniproenergo" – 79 refusals in 2020 against 60 compared to the same period in 2019 (an increase of 19 refusals), including due to the fault of staff 61 against 52 (an increase of 9):

Zaporizhzhia TPP – 24 refusals in 2020 against 20 compared to the same period in 2019 (an increase of 4 refusals), due to the fault of staff 17 vs. 16 (increase in)

"Kryvyi Rih TPP" – 35 refusals in 2020 against 19 compared to the same period in 2019 (an increase of 16 refusals), due to the fault of staff 24 against 19 (an increase of 5).

"Prydniprovska TPP" – 20 refusals in 2020 against 21 in comparison with the same period in 2019, due to the fault of staff 20 against 20.

PJSC Donbasenergo – 23 refusals in 2020 against 16 compared to the same period in 2019 (an increase of 7 refusals), including due to the fault of staff 18 vs. 14 (an increase of 4):

PJSC "Slavyansk TPP" – 23 refusals in 2020 against 16 compared to the same period in 2019 (an increase of 7 refusals), due to the fault of staff 18 against 14 (an increase of 4).

JSC DTEK Zakhidenergo – 77 refusals in 2020 against 94 compared to the same period in 2019, including the fault of staff 55 vs. 67:

"Dobrotvir TPP" – 19 refusals in 2020 against 24 compared to the same period in 2019, due to the fault of staff 18 vs. 14 (an increase of 4);

"Ladyzhynska TPP" – 27 refusals in 2020 against 28 compared to the same period in 2019 (an increase of 2 refusals) due to the fault of staff 16 against 19.

Burshtyn TPP – 31 refusals in 2020 against 42 compared to the same period in 2019, due to the fault of staff 21 vs. 34.

OJSC Centrenergo – 44 refusals in 2020 against 39 compared to the same period in 2019 (an increase of 5 refusals), including due to the fault of staff 7 vs. 5 (increase by 2):

Vuhlehirska TPP – 7 refusals in 2020 against 15 compared to the same period in 2019, including the fault of staff 0 against 4.

Zmiivska TPP – 20 refusals in 2020 against 16 compared to the same period in 2019 (an increase of 4 refusals), due to the fault of staff 4 against 1 (an increase of 3).

Trypilska TPP – 17 refusals in 2020 against 8 compared to the same period in 2019 (an increase of 9 refusals) due to the fault of staff 3 against 0 (an increase of 3).

DTEK Skhidenergo LLC – 68 refusals in 2020 against 48 compared to the same period in 2019 (an increase of 20 refusals), including the fault of staff 36 vs. 25 (an increase of 11):

"Kurakhovskaya TPP" – 55 refusals in 2020 against 30 compared to the same period in 2019 (an increase of 25 refusals) due to the fault of staff 29 against 18 (an increase of 11);

"Luhanska TPP" – 13 refusals in 2020 against 18 compared to the same period in 2019, due to the fault of staff 7 against 7.

DTEK Myronivska TPP LLC – 3 refusals in 2020 against 2 compared to the same period in 2019 (an increase of 1 refusal) without the fault of staff.

Separate CHP":

Pjsc "Mykolayiv CHPP" – 0 refusals in 2020 against 1 compared to the same period in 2019, including due to the fault of staff 0 vs. 1;

JSC "Odessa CHPP" – 0 refusals in 2020 against 1 compared to the same period in 2019, due to the fault of staff 0 vs. 1;

Pjsc "Kharkiv CHPP-5" – 9 refusals in 2020 against 6 compared to the same period in 2019 (an increase of 3 refusals) due to the fault of staff 3 against 0 (an increase of 1);

Branch "Teploelectrocentral" LLC "DV NGVK" (ESHAR) – 18 refusals in 2020 against 27 compared to the same period in 2019, due to the fault of staff 15 against 27;

SE "Kalush CHPP-Nova" – 1 refusal in 2020 against 2 compared to the same period in 2019, due to the fault of staff 0 vs. 1;

Kremenchug CHPP LLC – 3 refusals in 2020 against 6 compared to the same period in 2019, including the fault of staff 3 vs. 4;

"Cherkasy CHP" pjsc "Cherkasy chemical fiber" – 3 refusals in 2020 against 11 in comparison with the same period in 2019, due to the fault of staff 2 against 8;

CEP "Chernigov CHP" LLC Firm "TEHNOVA" – 9 refusals in 2020 against 2 compared to the same period in 2019 (an increase of 7 refusals) due to the fault of personnel 9 against 1 (an increase of 8);

LLC "Euro-reconstruction" (Darnytska CHPP) – 4 refusals in 2020 against 3 compared to the same period in 2019 (an increase of 1 refusal) due to the fault of staff 4 against 3 (an increase of 1);

KP "Kyivteploenergo" – 7 refusals in 2020 against 3 compared to the same period in 2019 (an increase of 4 refusals), including due to the fault of staff 2 against 0 (increase by 2):

Kyiv CHPP-5 – 7 refusals in 2020 against 3 compared to the same period in 2019 (an increase of 4 refusals) due to the fault of staff 2 against 0 (increase by 2);

Kyiv CHPP-6 – 0 refusals in 2020 against 0 compared to the same period in 2019, due to the fault of staff 0 vs. 0;

Pjsc "Ukrhydroenergo" – 7 refusals in 2020 against 5 compared to the same period in 2019, due to the fault of staff 2 vs. 2:

Branch "Directorate for construction of The Dniester PSP" – 3 refusals in 2020 against 1 compared to the same period in 2019 (an increase of 2 refusals) without the fault of the staff;

Branch "Dniprovska HPP" – 1 refusal in 2020 against 1 compared to the same period in 2019, due to the fault of personnel 1 vs. 1;

Branch "Srednedniprovska HPP" – 1 refusal in 2020 against 0 compared to the same period in 2019 (an increase of 1 refusal), without the fault of staff:

Branch "Kakhovka HPP them. P.S. Neporozhny" – 0 refusals in 2020 against 1 compared to the same period in 2019, without the fault of the staff;

Branch "Kremenchug HPP" – 0 refusals in 2020 against 1 compared to the same period in 2019, the fault of the staff is 0 vs. 1;

Branch "Cascade of Kyiv hydroelectric power plants and hydroelectric power plants" – 2 refusals in 2020 against 0 compared to the same period in 2019 (an increase of 2 refusals), the fault of staff 1 against 0 (an increase of 1);

Branch "Dniester HPP" – 0 refusals in 2020 against 1 compared to the same period in 2019, without the fault of the staff.

Pjsc NPC "Ukrenergo" – 101 refusals in 2020 against 72 comparable to the same period in 2019 (an increase of 29 refusals), including due to the fault of staff 9 against 10:

VP "Dniprovska ES" – 31 refusals in 2020 against 17 compared to the same period in 2019 (an increase of 14), due to the fault of staff 5 against 5;

"Western EU" – 11 refusals in 2020 against 13 compared to the same period in 2019, due to the fault of staff 0 against 1;

"Southern EU" – 11 refusals in 2020 against 9 compared to the same period in 2019 (an increase of 2), due to the fault of staff 1 against 0 (an increase of 1);

"South-Western EU" – 4 refusals in 2020 against 11 compared to the same period in 2019, without the fault of staff;

"Northern EU" – 35 refusals in 2020 against 15 compared to the same period in 2019 (an increase of 20), due to the fault of staff 3 against 4;

"Central EU" – 9 refusals in 2020 against 7 compared to the same period in 2019 (an increase of 2), without the fault of staff;

SE NNEGC "Energoatom" – 5 refusals in 2020 against 11 compared to the same period in 2019, including the fault of staff 0 vs. 2:

Rivne NPP – 1 refusal in 2020 against 2 compared to the same period in 2019, due to the fault of staff 0 vs. 2;

Khmelnitsky NPP – 0 refusals in 2020 against 0 compared to the same period in 2019, due to the fault of staff 0 vs. 0;

"South Ukrainian NPP" – 1 refusal in 2020 against 2 compared to the same period in 2019, due to the fault of staff 0 vs. 0;

Zaporizhzhia NPP – 1 refusal in 2020 against 1 comparable to the same period in 2019, due to the fault of staff 0 vs. 0;

Tashlyk PSP – 2 refusals in 2020 against 6 comparable to the same period in 2019 (an increase of 4 refusals), including the fault of staff 0 against 0.

Annex B

Table B1. Shadow prices of one minute of interruption (€ cents), 2013–2015.

DSO	2013	2014	2015	DSO	2013	2014	2015
Äänekosken Energia Oy	0.454	0.449	0.457	Lehtimäen Sähkö Oy	0.457	0.461	0.443
Alajärven Sähkö Oy	0.447	0.466	0.278	Leppäkosken Sähkö Oy	0.457	0.470	0.468
Caruna Espoo Oy	0.462	0.472	0.474	LE-Sähköverkko Oy	0.477	0.481	0.482
Caruna Oy	0.348	0.447	0.439	Mäntsälän Sähkö Oy	0.458	0.474	0.467
Ekenäs Energi Ab	0.477	0.470	0.471	Muonion Sähköosuuskunta	0.426	0.343	0.035
Elenia Oy	0.295	0.445	0.209	Naantalin Energia Oy	0.479	0.479	0.481
Enontekiön Sähkö Oy	0.000	0.357	0.337	Nurmijärven Sähköverkko Oy	0.463	0.474	0.469
ESE-Verkko Oy	0.480	0.482	0.479	Nykarleby Kraftverk Ab	0.429	0.422	0.426
Esse Elektro-Kraft Ab	0.416	0.452	0.286	Oulun Energia Siirto ja Jakelu Oy	0.468	0.470	0.472
Etelä-Suomen Energia Oy	0.364	0.399	0.433	Oulun Seudun S. Verkkopalvelut Oy	0.452	0.467	0.443
Forssan Verkkopalvelut Oy	0.481	0.482	0.482	Outokummun Energia Oy	0.457	0.432	0.462
Haminan Energia Oy	0.478	0.480	0.476	Paneliankosken Voima Oy	0.414	0.472	0.466
Haukiputaan Sähköosuuskunta	0.471	0.474	0.478	Parikkalan Valo Oy	0.179	0.444	0.349
Helen Sähköverkko Oy	0.483	0.483	0.482	Pellon Sähkö Oy	0.465	0.449	0.440
Herrfors Nät-Verkko Oy Ab	0.347	0.433	0.384	PKS Sähkönsiirto Oy	0.376	0.376	0.066
Iin Energia Oy	0.477	0.478	0.459	Pori Energia Sähköverkot Oy	0.386	0.440	0.449
Imatran Seudun Sähkönsiirto Oy	0.268	0.448	0.394	Porvoon Sähköverkko Oy	0.399	0.439	0.449

Continuation of Table B1

Järvi-Suomen Energia Oy	0.242	0.438	0.319	Raahen Energia Oy	0.482	0.480	0.481
Jeppo Kraft Andelslag	0.454	0.453	0.445	Rantakairan Sähkö Oy	0.465	0.466	0.456
JE-Siirto Oy	0.481	0.480	0.482	Rauman Energia Oy	0.445	0.475	0.463
Jylhän Sähköosuuskunta	0.457	0.474	0.435	Rovakaira Oy	0.413	0.452	0.431
Karhu Voima Oy	0.481	0.477	0.464	Rovaniemen Verkko Oy	0.480	0.480	0.474
Kemin Energia Oy	0.478	0.479	0.467	Sallila Sähkönsiirto Oy	0.434	0.466	0.465
Keminmaan Energia Oy	0.446	0.478	0.371	Savon Voima Verkko Oy	0.175	0.287	0.146
KENET Oy	0.469	0.473	0.476	Seiverkot Oy	0.470	0.475	0.476
Keravan Energia Oy	0.472	0.468	0.479	Tampereen Sähköverkko Oy	0.449	0.478	0.450
Keuruun Sähkö Oy	0.355	0.414	0.378	Tenergia Oy	0.405	0.427	0.391
Koillis-Lapin Sähkö Oy	0.371	0.445	0.447	Tornion Energia Oy	0.469	0.473	0.447
Koillis-Satakunnan Sähkö Oy	0.441	0.443	0.415	Tornionlaakson Sähkö Oy	0.418	0.463	0.436
Kokemäen Sähkö Oy	0.425	0.466	0.468	Tunturiverkko Oy	0.443	0.451	0.412
Köyliön-Säkylän Sähkö Oy	0.452	0.469	0.473	Turku Energia Sähköverkot Oy	0.469	0.481	0.481
Kronoby Elverk Ab	0.440	0.410	0.459	Vaasan Sähköverkko Oy	0.417	0.430	0.434
KSS Verkko Oy	0.454	0.455	0.470	Vakka-Suomen Voima Oy	0.352	0.458	0.430
Kuopion Sähköverkko Oy	0.481	0.481	0.478	Valkeakosken Energia Oy	0.476	0.476	0.108
Kymenlaakson Sähköverkko Oy	0.375	0.426	0.391	Vatajankosken Sähkö Oy	0.419	0.455	0.451
Lammaisten Energia Oy	0.457	0.473	0.475	Verkko Korpela Oy	0.323	0.253	0.378
Lankosken Sähkö Oy	0.274	0.410	0.384	Vetelin Sähkölaitos Oy	0.431	0.474	0.135
Lappeenrannan Energiaverkot Oy	0.401	0.455	0.437	Vimpelin Voima Oy	0.359	0.446	0.360

Continuation of Table B1

Kuoreveden Sähkö Oy	0.445	0.468	0.418	Vantaan Energia Sähköverkot Oy	0.479	0.480	0.481

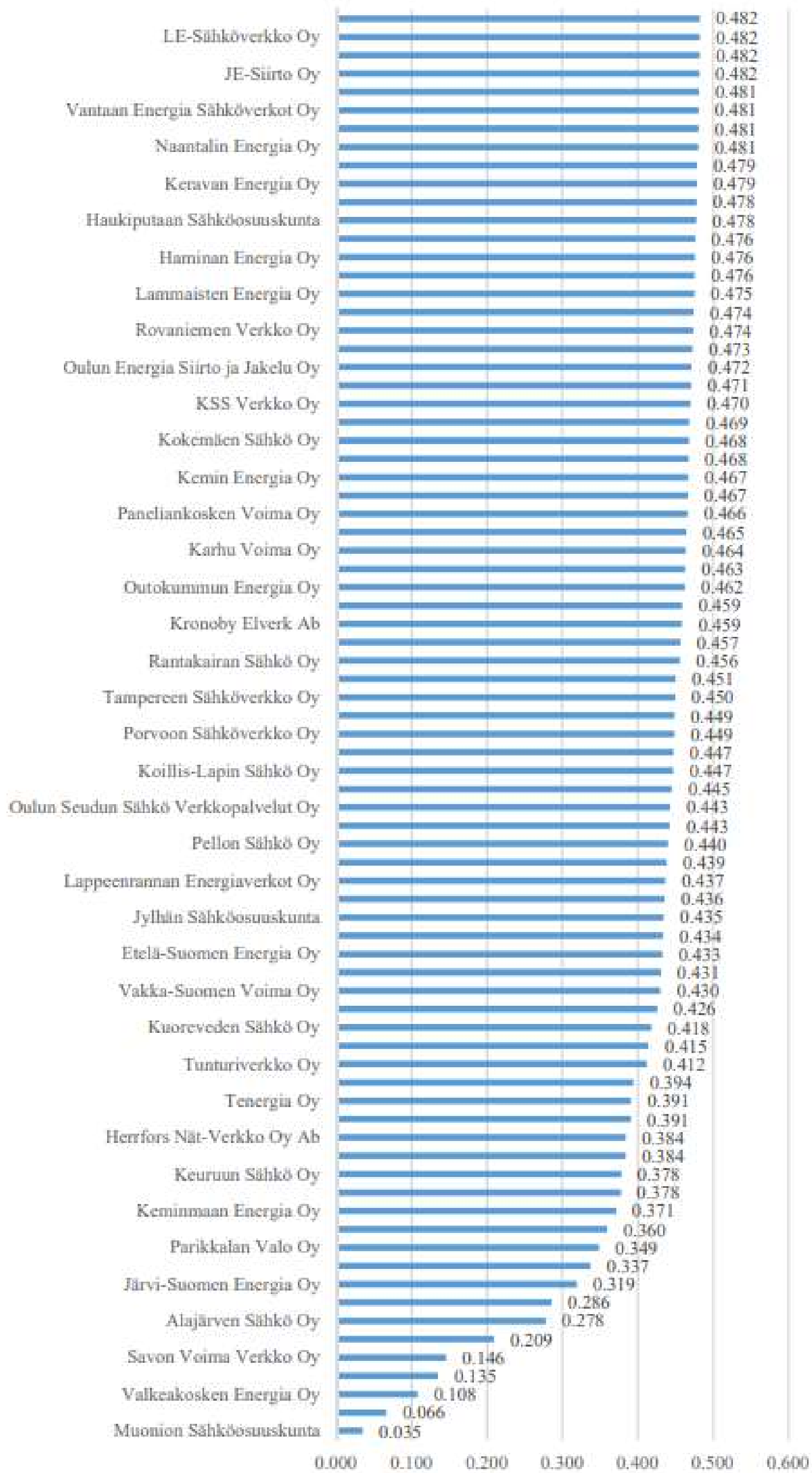

Figure B1 Shadow price of power outages in 2015

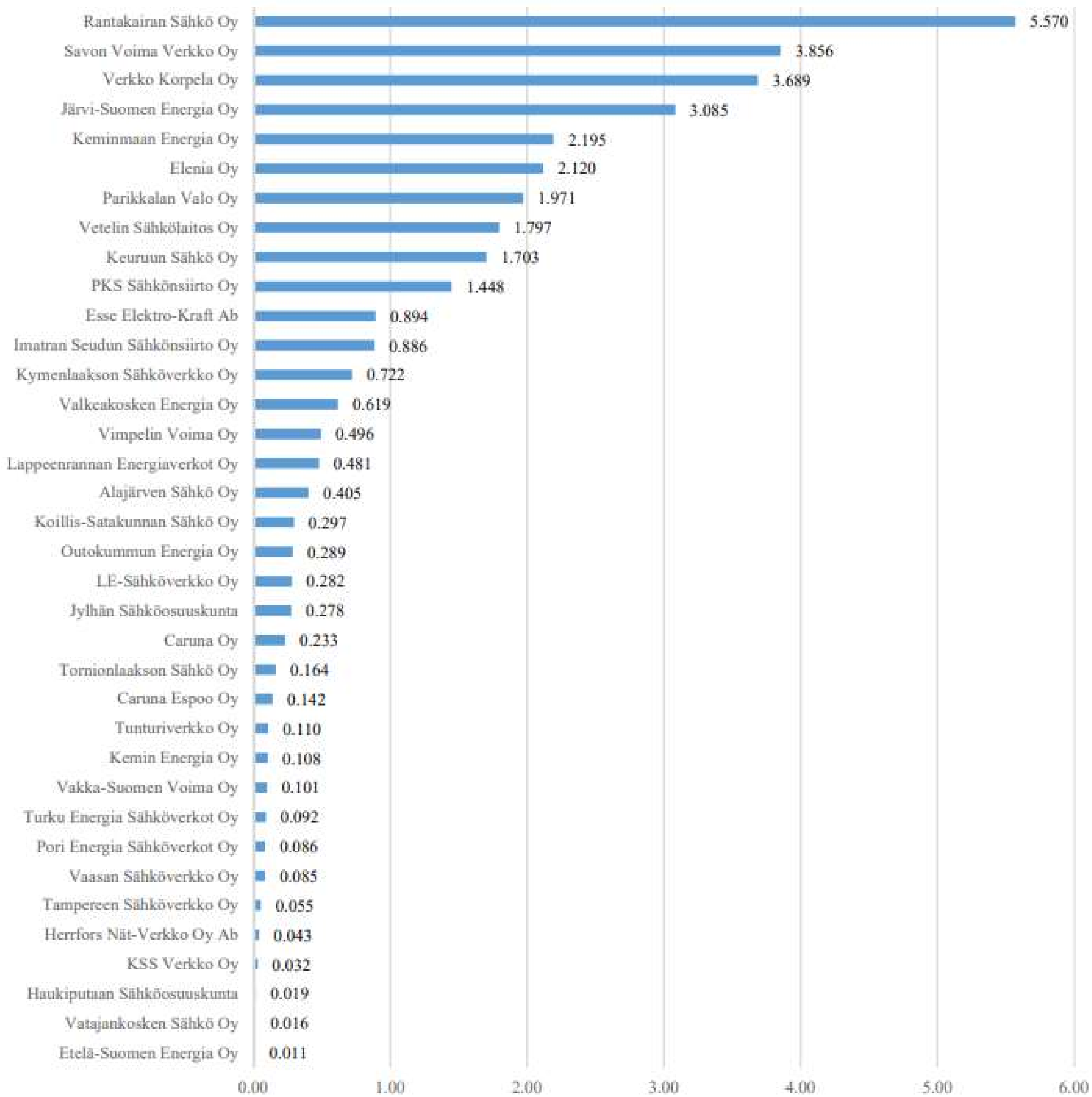

Figure B2. Compensation price of one minute of interruption during 2015 (€ cents).

Annex C

Data for calculations for the establishment of discounts for the participation of consumers in reducing electricity shortages

Table C.1. Performance indicators of thermal power plants in Ukraine

№	Names of stations	Maximum operating capacity of thermal power plants, thousand kW	The coefficient of use of working blocks of stations, %
1	Ladyzhynska TPP	1300	16,6666667
2	Kryvyi Rih TPP	1890	14,2857143
3	Zaporizhzhya TPP	1590	66,6666667
4	Prydniprovska TPP	1280	40
5	Vuhlehirska TPP	1640	14,2857143
6	Slavyansk TPP	600	50
7	Luhanska TPP	500	0
8	Kurakhovskaya TPP	1050	71,4285714
9	Trypilska TPP	600	33,333
10	Burshtyn TPP	2351	75
11	Dobrotvir TPP	395	100
12	Zmiivska TPP	1500	10
13	Kyiv CHPP-5	264	50
14	Kyiv CHPP-6	300	50
15	Kharkiv CHPP-5	300	66,6666

Table C.2 Distribution of states of generating part of power system and probability of their occurrence

Blocks in working order	Blocks in downtime	Probability of system state	State of the system thousand kW
75	0	1,29E-30	21842
74	1	1,32E-28	21551
73	2	6,63E-27	21260
72	3	2,20E-25	20969
71	4	5,44E-24	20678
70	5	1,06E-22	20387
69	6	1,70E-21	20096
68	7	2,32E-20	19805
67	8	2,74E-19	19514
66	9	2,83E-18	19223
65	10	2,61E-17	18932
64	11	2,16E-16	18641
63	12	1,61E-15	18350
62	13	1,10E-14	18059
61	14	6,91E-14	17768
60	15	3,99E-13	17477
59	16	2,13E-12	17186
58	17	1,06E-11	16895
57	18	4,89E-11	16604
56	19	2,12E-10	16313
55	20	8,58E-10	16022
54	21	3,27E-09	15731
53	22	1,17E-08	15440
52	23	3,97E-08	15149
51	24	1,27E-07	14858
50	25	3,84E-07	14567
49	26	1,10E-06	14276
48	27	2,99E-06	13985

Continuation of table C.2

48	27	2,99E-06	13985
47	28	7,73E-06	13694
46	29	1,90E-05	13403
45	30	4,44E-05	13112
44	31	9,89E-05	12821
43	32	0,000209963	12530
42	33	0,000425371	12239
41	34	0,000822715	11948
40	35	0,001519996	11657
39	36	0,002683966	11366
38	37	0,004531682	11075
37	38	0,007319359	10784
36	39	0,011313068	10493
35	40	0,016738764	10202
34	41	0,023715081	9911
33	42	0,032180138	9620
32	43	0,041831057	9329
31	44	0,052098521	9038
30	45	0,062175342	8747
29	46	0,071106748	8456
28	47	0,077932757	8165
27	48	0,081855122	7874
26	49	0,082389434	7583
25	50	0,079462718	7292
24	51	0,07342956	7001
23	52	0,065001907	6710
22	53	0,055111637	6419
21	54	0,044742347	6128
20	55	0,034772019	5837
19	56	0,025860368	5546
18	57	0,018398008	5255

Continuation of table C.2

30	45	0,062175342	8747
29	46	0,071106748	8456
28	47	0,077932757	8165
27	48	0,081855122	7874
26	49	0,082389434	7583
25	50	0,079462718	7292
24	51	0,07342956	7001
23	52	0,065001907	6710
22	53	0,055111637	6419
21	54	0,044742347	6128
20	55	0,034772019	5837
19	56	0,025860368	5546
18	57	0,018398008	5255
17	58	0,012515682	4964
16	59	0,00813729	4673
15	60	0,005053784	4382
14	61	0,002996471	4091
13	62	0,001695031	3800
12	63	0,00091413	3509
11	64	0,000469633	3218
10	65	0,000229642	2927
9	66	0,000106776	2636
8	67	4,72E-05	2345
7	68	1,98E-05	2054
6	69	7,85E-06	1763
5	70	2,95E-06	1472
4	71	1,05E-06	1181
3	72	3,51E-07	890
2	73	1,11E-07	599
1	74	3,27E-08	308
0	75	9,09E-09	0

Table C.3 Average Annual Values for Marginal Price, Operating Capacity and Wholesale Purchase Price of Electricity

Hour of a day	The price of DAM UAH/kW.h	Price of IDM UAH/kW.h	Weighted average wholesale price of electricity UAH/kWh
1	1385,727	1378,43	1382,078
2	931,8584	924,2852	928,0718
3	846,3939	835,4852	840,9395
4	841,4506	829,4116	835,4311
5	852,0477	841,0387	846,5432
6	883,3984	872,8623	878,1303
7	1283,013	1275,918	1279,465
8	2745,786	2705,299	2725,543
9	3192,397	3159,051	3175,724
10	3356,474	3330,713	3343,593
11	3258,301	3244,789	3251,545
12	3236,37	3206,626	3221,498
13	3197,399	3160,395	3178,897
14	3238,196	3200,649	3219,423
15	3301,328	3263,256	3282,292
16	3404,205	3361,129	3382,667
17	3670,351	3625,36	3647,855
18	3765,012	3728,086	3746,549
19	3726,943	3682,132	3704,537
20	3640,11	3591,201	3615,656
21	3562,579	3508,122	3535,35
22	3451,122	3401,205	3426,164
23	3203,68	3148,104	3175,892
24	1575,785	1559,306	1567,545