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MUNDARIJA

RAQAMLI IQTISODIYOTDA TADBIRKORLIK SUBYEKTLARI FAOLIYATINING IQTISODIY XAVFSIZLIGIGA TA'SIR ETUVCHI TIZIMLASHTIRILGAN TAHDIDLAR.....	40
Qodirov Tuyg'un Uzoqovich, Nabiyev Bexzod Shavkatovich	
SANOAT TARMOQLARINI RIVOJLANTIRISHDA INNOVATSIYA VA TEXNOLOGIK MODERNIZATSIYANING O'RNI	44
Boboqulov Sanjar Bahromqulovich	
YASHIRIN IQTISODIYOTNI BAHOLASHNING USLUBIYOTI VA UNING SOLIQ TIZIMIDA QO'LLANILISHI	49
To'xtabayev Oybek Odilovich	
YASHIRIN IQTISODIYOTNI QISQARTIRISHDA RAQAMLI TEXNOLOGIYALARDAN FOYDALANISH BO'YICHA ILG'OR XORIJIY TAJRIBALAR.....	56
Ismailov Bobir Salomovich	
TIJORAT BANKLARI INVESTITSIYA FAOLIYATINI RIVOJLANTIRISHNING ILMIY-NAZARIY JIHATLARI	62
Yangiboyev F.B.	
MINTAQAVIY IQTISODIY SALOHİYATDAN FOYDALANISH SAMARADORLIGINI BAHOLASH.....	68
Turayev Og'abek Kaxramonovich	
XORIJIY MAMLAKATLARDA TO'QIMACHILIK KLASTERLARINI RIVOJLANTIRISH TAJRIBASI.....	75
Yusupova Feruza Yo'ldoshevna	
BANK XIZMATLARI SIFATINI BOSHQARISHNING INTEGRATSION VA ADAPTIV MODEL.....	83
Ibroximov Ilxomjon Shavkatjon o'g'li	
QURILISH TASHKILOTLARI FAOLIYATINING MOLIYAVIY BARQARORLIGINI EKONOMETRIK MODELLAR ASOSIDA BAHOLASH	89
Qidirniyazov Ajiniyaz Sherniyazovich	
ICHKI NAZORAT VA KORPORATIV BOSHQARUV TIZIMIDAGI XAVFLARNI BOSHQARISH	94
Islamova Nargiza Mirzaxidovna	
TURIZMNING MINTAQADA IQTISODIY RIVOJLANISHIGA TA'SIRI	104
Rasulova Muxabbat Teshabayevna, Normurodov Sarvar Norboy o'g'li	
O'ZBEKISTONDA INVESTITSIYALARNI JALB QILISH ORQALI INVESTITSION JOZIBADORLIKNI OSHIRISHNING HOZIRGI KUNDAGI HOLATI TAHLILI	111
Begamov S.X.	
RETHINKING JOB CREATION: ONTOLOGICAL AND EPISTEMOLOGICAL FOUNDATIONS OF MACROECONOMIC EMPLOYMENT ANALYSIS.....	116
Zakhidov Azizbek Rustamovich	
HUDUDIY TURIZM KLASTERLARINI SHAKLLANTIRISH VA ULARNING IQTISODIY SAMARADORLIGINI OSHIRISH.....	125
Ro'zimova Xusnora Mirzobek qizi	
SUG'URTACHILIK VA O'ZBEKISTONDA SUG'URTA SEKTORINING HOLATI.....	129
O'runboyeva Sotima Alisher qizi	
GO'SHT VA GO'SHT MAHSULOTLARINI SANOAT USULIDA QAYTA ISHLASHDA XORIJIY MAMLAKATLAR TAJRIBALARI.....	134
Kaydarova Sitora Suranbay qizi	
KORXONALAR QIYMATINI BAHOLASH VA BOZOR BAHOSINI SHAKLLANTIRISH METODOLOGIYASI.....	139
Abduraxmanov Sherzodbek Ravshanovich	
YASHIL IQTISODIYOT: EKOLOGIK BARQARORLIK VA IQTISODIY SAMARADORLIK UYG'UNLIGI.....	145
Jamaldinova Asalxon Saliyevna	
2025-YILDA O'ZBEKISTON UCHUN ENG YAXSHI 10 TA TRANSPORT TEXNOLOGIYALARI VA INNOVATSIYALARI	151
Mamasaliyeva Mukaddas Ibadullayevna, Beketov Timur Kazakbayevich	



MAHSULOT TANNARXINI ANIQLASHNING INTEGRATSIYALASHGAN YONDASHUVLARI: AN'ANAVIY VA ZAMONAVIY TIZIMLAR QIYOSIY TAHLILI	155
Tulyaganov Abdumalik Abdiraximovich	
ИННОВАЦИОННО-ИНВЕСТИЦИОННАЯ ДЕЯТЕЛЬНОСТЬ В НАЦИОНАЛЬНОЙ ЭКОНОМИКЕ: ИНТЕРПРЕТАЦИЯ ТЕОРЕТИЧЕСКИХ ПОДХОДОВ	163
Хайдарова Ёркиной Аскар кизи	
RAQAMLI IQTISODIYOT SHAROITIDA INNOVATSION TADBIRKORLIKNI QO'LLAB-QUVVATLASHNING FISKAL VA INSTITUTSIONAL MEKANIZMLARI	170
Mamatova Nodira Mirzavaliyevna	
ЗЕЛЕНАЯ ЭКОНОМИКА И УСТОЙЧИВЫЕ ИНВЕСТИЦИИ: ФОРМИРОВАНИЕ ИНВЕСТИЦИОННОЙ МОДЕЛИ ПЕРЕХОДА ТЕПЛИЧНЫХ ХОЗЯЙСТВ ТАШКЕНТСКОЙ АГЛОМЕРАЦИИ НА СОЛНЕЧНЫЕ СИСТЕМЫ ЭНЕРГОСНАБЖЕНИЯ	178
Срджиддинова Зарина Хайриддиновна, Абдувалиева Зилола Абдуллаевна	
МАМЛАКАТИМИЗДА QISHLOQ HUDUDLARIDA XIZMATLAR SOHASINI RIVOJLANTIRISHNING AHAMIYATI	186
Yuldashova Nilufar Ziyabayevna	
RIVOJLANISHDA RAQOBAT EMAS, BALKI HAMKORLIKNING USTUVORLIGI: NAZARIY VA AMALIY TAHLIL	190
Xolmirzayev Ulug'bek Abdulazizovich	
IJTIMOY HIMOYA QAMROVINI KENGAYTIRISH MEKANIZMLARI VA "QAMRAB OLINMAGAN O'RTA QATLAM" MUAMMOSI	196
Bafoev Farrux Jo'raqulovich	
RAQAMLI TEXNOLOGIYALAR YORDAMIDA EKOLOGIK BOSHQARUVNI TAKOMILLASHTIRISH	202
Shanazarova Gulyoraxon Baxtiyarovna	
O'ZBEKISTON STARTAP EKOTIZIMIDA INVESTITSIYA JALB QILISH JARAYONINING INSTITUTSIONAL MUAMMOLARI VA ULARNI BARTARAF ETISH MEKANIZMLARI	208
Xoliqova Xurshidaxon Xayotjon qizi	
INNOVATSION IQTISODIYOTNI RIVOJLANTIRISH SHAROITIDA STARTAP EKOTIZIMINI SHAKLLANTIRISHNING NAZARIY JIHLTLARI	214
Usmanov Gafurjon Shavkatovich	
QURILISHDA ISHLAB CHIQRISH VA SIFATNI BOSHQARISH TIZIMLARINING RIVOJLANISHI	220
Buriyev Xakim Toshimovich, Usmanov Ilxom Achilovich	
O'ZBEKISTONDA INVESTITSION MUHITNI TAKOMILLASHTIRISHNING STRATEGIYALARI	225
Xolov Sherali Axrorboyevich	
2010-2024-YILLARDA O'ZBEKISTONDA TO'QIMACHILIKNI INVESTITSIYALASHNING EKONOMETRIK TAHLILI	229
Ashurov Shuhratbek Qudrat o'g'li	
TIJORAT BANKLARI MOLIVAVIY XAVFSIZLIGINI TA'MINLASHNING ZAMONAVIY USULLARI	233
Sherbekova Kamola Norbekovna	
AHOLI MOLIVAVIY SAVODXONLIGI DARAJASI VA UNI BAHOLASHNING ILMIY-USLUBIY ASOSLARI	243
Abduvoxidov Akmal Abdulazizovich	
MARKAZIY BANK KURS SIYOSATI SAMARADORLIGINI OSHIRISH USULLARI	249
Saydullayev Nodirbek Narzullaevich	
O'ZBEKISTON MINTAQALARIDA BARQAROR TURIZMNI RIVOJLANTIRISH SALOHİYATI VA MUAMMOLARI	258
Raupov Shuxrat Soyibovich	
ЭКОТУРИЗМ В УЗБЕКИСТАНЕ: СОВРЕМЕННОЕ СОСТОЯНИЕ И ПЕРСПЕКТИВЫ УСТОЙЧИВОГО РАЗВИТИЯ	264
Абидова Дилфуза Игамбердиевна, Рахматуллаева Зулайхо Хасан кизи	
DIGITAL ECONOMY AND ARTIFICIAL INTELLIGENCE: BUSINESS CHANGE IN THE REGIONS	270
Abdullayev Muzaffar Abdujabbarovich	



QISHLOQ XO'JALIK MAHSULOTLARINI QAYTA ISHLASHDA IOT TEXNOLOGIYALARIDAN FOYDALANISH.....	273
Mirzaev Dilshod Artikovich	
ПРАКТИЧЕСКИЕ АСПЕКТЫ ПРИМЕНЕНИЯ МЕХАНИЗМОВ ФИНАНСИРОВАНИЯ СТАРТАП-ПРОЕКТОВ В ВУЗАХ УЗБЕКИСТАНА.....	279
Касимова Наргиза Сабитджановна	
YASHIL IQTISODIYOTNING NAZARIY ASOSLARI VA UNGA ILMIY YONDASHUVLAR.....	284
Ismoyilova Mahliyo Oybek qizi	
BOSHQARUVDA ZAMONAVIY YONDASHUVLAR (OLIV TA'LIM MISOLIDA).....	289
Kariyeva Gulnora Abdullayevna, Normurodov Sarvar Norboy o'g'li	
TIJORAT BANKLARIDA KORPORATIV MIJOZLARGA XIZMAT KO'RSATISHNING AMALDAGI HOLATI VA ASOSIY TENDENSIYALARI.....	295
Qurbonov Odilbek Ro'zmatovich	
O'ZBEKISTONDA SPORT FEDERATSIYALARI VA ASSOTSIATSIYALARINI SAMARALI BOSHQARISH TIZIMINI MODERNIZATSIYA QILISH YO'LLARI.....	302
Umed Farmonkulovich Radjabov	
XIZMAT KO'RSATISH KORXONALARI FAOLIYATI SAMARADORLIGINI OSHIRISHGA QARATILGAN IQTISODIY MEKANIZMNI TAKOMILLASHTIRISHNING USTUVOR YO'NALISHLARI VA ULARNING AMALIY AHAMIYATI.....	307
Mullayeva Mexrangiz Axtam qizi	
KICHIK BIZNESNI RIVOJLANTIRISHNING IQTISODIY MUAMMOLARI VA ULARNI BARTARAF ETISH YO'LLARI (NAMANGAN VILOYATI MISOLIDA).....	313
Xolmirzayev Ulug'bek Abdulazizovich, Muradova Nazira Raximjanovna	
RAQAMLI MARKETING VA ONLAYN PLATFORMALAR ORQALI EKOTURISTIK MAJMUALARNI OMMALASHTIRISH TRENDI.....	318
Xolmatova Parvina Asliddin qizi	
O'ZBEKISTONDA SOLIQ MA'MURCHILIGI STRATEGIYASINI TAKOMILLASHTIRISH MASALALARI VA ULARNI YECHIMLAR.....	323
Normurzayev Umid Xolmurzayevich	
РАЗВИТИЕ ДИСТАНЦИОННОГО БАНКОВСКОГО ОБСЛУЖИВАНИЯ В ХОРЕЗМСКОЙ ОБЛАСТИ НА ОСНОВЕ ТЕХНОЛОГИЙ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА КАК ФАКТОР РЕГИОНАЛЬНОГО ЭКОНОМИЧЕСКОГО РОСТА.....	327
Бахтиёров Худайберган Хамдам угли	
MAHALLIY BUDJETLARDA TRANSFERTLARGA QARAMLIK DARAJASINI BAHOLASH (XORAZM VILOYATI MISOLIDA).....	335
Xudoyqulov Hamidjon Abdullayevich	
QORAQALPOG'ISTON QISHLOQ XO'JALIGIDA RESURSLARDAN SAMARALI FOYDALANISHNI BOSHQARISHNING INNOVATSION YONDASHUVLARI.....	342
Tajibaev Berdax Asqarbay uli	
XIZMAT KO'RSATISH SOHASIDA INNOVATSION JARAYONLARNI JADALLASHTIRISH MEKANIZMLARINI TAKOMILLASHTIRISH.....	347
Ashurova Maftuna Ortiq qizi	
STRATEGIC DIRECTIONS FOR INCREASING CAPITAL EFFICIENCY OF COMMERCIAL BANKS: DIGITALIZATION AND RISK MANAGEMENT INTEGRATION.....	352
Sadullaeva Mokhinur Aziz kizi	
TECHNOLOGY MANAGEMENT AND SME INTERNATIONALIZATION: A SYSTEMATIC LITERATURE REVIEW.....	358
Abduxafizova Madinabonu Mirabbos qizi	
TA'LIM SIFATINI BAHOLASH MEZONLARINI SHAKLLANTIRISH USULLARI.....	363
Mamadiyarov Zokir Toshmurovich	
SMART UNIVERSITET KONSEPSIYASI ASOSIDA REYTING VA RAQOBATBARDOSHLIKNI INTEGRAL BOSHQARISH.....	371
Xudoyqulov Husen Ahadovich	



BUXGALTERIYA HISOBINING MILLIY VA XALQARO STANDARTLARI ASOSIDA MOLIVAVIY HISOBOT 1-SHAKLINING QIYOSIY TAHLILI	379
Shodiyev Murodjon Bakirovich	
SUG'URTA BOZORINING RAQAMLI RIVOJLANISHIDA NAZARIY QARASHLAR	384
G'oziyeva Aziza Abdusalomovna	
MINTAQAVIY IQTISODIY RIVOJLANISHDA INNOVATSION LOYIHALAR SAMARADORLIGINI BAHOLASH USULLARI	389
Xamrayev Quvvat Iskandarovich	
MAHALLIY BUDJETLAR DAROMADLARINI SHAKLLANTIRISHNING IQTISODIY AHAMIYATI	397
P.SH.Usmonov	
СРАВНИТЕЛЬНАЯ ХАРАКТЕРИСТИКА МЕТОДОВ ИНВЕСТИЦИОННОГО АНАЛИЗА ДЛЯ ОЦЕНКИ ДОХОДНОСТИ АКЦИЙ УЗБЕКСКИХ ЭМИТЕНТОВ.....	401
Ирмухамедова Муслима Дилшодовна	
KORXONA VA TASHKILOTLARDA INSON KAPITALIDAN SAMARALI FOYDALANISHDA KORPORATIV MADANIYAT, AXLOQIY-RUHIY VA MA'NAVIY MUHITNING O'RNI	407
Suyunov Dilmurod Xolmurodovich, Qodirov Tuyg'un Uzoqovich	
ELEKTRON PULLARNING MOHIYATI VA ULARNING MILLIY TO'LOV TIZIMIDAGI ROLI.....	416
Toshniyozov Sherali Kamoliddinovich	
RAQAMLI IQTISODIYOT SHAROITIDA UY XO'JALIKLARINING TADBIRKORLIK FAOLIYATINI KENGAYTIRISH.....	423
Eshbaeva Shahnoza Faxriddinovna	
APPLICATION OF EXTREME MODELS IN ASSESSING THE ECONOMIC POTENTIAL OF AN ENTERPRISE	428
Musayeva Shoira Azimovna	
SOLIQ MA'MURCHILIGIDA XORIJIY TAJRIBA HAMDA UNI O'ZBEKISTONDA QO'LLASH SAMARADORLIGI.....	435
Bozorova Ozoda Raximovna	
DAVLAT FUQAROLIK XIZMATI IMIJINI OSHIRISHDAGI MUAMMOLARNI HAL ETISHDA XORIJIY DAVLATLAR TAJRIBASI: QIYOSIY TAHLIL.....	439
Bekmurodov Navruz Ergashevich	
TA'LIM XIZMATLARI SOHASIDA YARATILGAN YALPI QO'SHILGAN QIYMAT DINAMIKASI VA UNI BOSHQARISH MEXANIZMLARINI TAKOMILLASHTIRISH.....	449
O'rinov Komiljon Kozimovich	
BARQAROR RIVOJLANISHNI TA'MINLASHNING MINTAQAVIY OMILLARI.....	453
Salomat Norova	
QURILISH MATERIALLARI BOZORI VA UNI RIVOJLANTIRISHNING NAZARIY ASOSLARI	459
Usubjonov Zaxriddin Vasliddin o'g'li	
O'ZBEKISTON RESPUBLIKASIDA EKSPORT OPERATSIYALARINI SUG'URTA QILISHNI RIVOJLANTIRISH.....	465
Xalikov R. B.	
BIZNES JARAYONLAR AUTSORSINGINI OPTIMALLASHTIRISH USULLARI TAHLILI	472
Uzaqov Ortik Shaymardanovich	
DAVLAT MOLIVAVIY BOSHQARUVI SAMARADORLIGINING IJTIMOY ADOLATGA TA'SIRINING PEFA VA CEQ METODOLOGIYALARI ORQALI TAHLILI	477
Zokirjonov Muhammadsodiq Ravshanbek o'g'li	
NODAVLAT OLIY TA'LIM MUASSASALARIDA ICHKI AUDIT XIZMATINI TASHKIL QILISHNING XORIJ TAJRIBASI	485
Turmanqulov Norpo'lat Sa'dullayevich	
MINTAQADA IJTIMOY HIMOYA TIZIMINI TAKOMILLASHTIRISH ORQALI KAMBAG'ALLIKNI QISQARTIRISH.....	491
Saparov Ismat Chorshanbiyevich	
MINTAQANI BARQAROR RIVOJLANISHDA EKOLOGIK INNOVATSIYALARNI QO'LLAB-QUVVATLASH YO'NALISHLARI	495
Ismatov Sharofiddin Asatulloevich	



THE ESSENCE OF THE OPTIMAL COST STRATEGY	500
Sodiqov Mirakhror Abbos ugli	
TURIZMNI RIVOJLANTIRISHDA TOG'-KURORT ZONALARINI RIVOJLANTIRISHNING IQTISODIY JIHATLARI (CHORVOQ ERKIN TURISTIK ZONASI MISOLIDA)	504
Shomurodova Shahnoza G'ayratovna	
ICHKI AUDIT SIFATI VA SAMARADORLIGI TUSHUNCHALARINING IQTISODIY MAZMUNI HAMDA ULARNING O'ZARO BOG'LIQLIGI	509
Ergashev Olloyor Furqat o'g'li	
QISHLOQ XO'JALIGI KORXONALARI FAOLIYATINI SOLIQQA TORTISH VA UNI HISOBINI YURITISH.....	517
Abdullayev Abdurauf	
TIJORAT BANKLARINING RISKLARINI BAHOLASHDA ZAMONAVIY YONDASHUVLAR.....	522
Kudaybergenova Guzal Kuanishbayevna	
TIJORAT BANKLARIDA KORRUPSIYAVIY-KOMPLAENS MUAMMOLARI: TAHLIL VA YECHIMLAR.....	527
Yunusov Baxtiyor Shavkatovich	
MAISHIY XIZMAT KO'RSATISHNING SIFAT NAZORATINI HAMDA TASHKILIIY-IQTISODIY MEKANIZMINI TAKOMILLASHTIRISH	532
Meliyev X.T.	
ОЦЕНКА КАЧЕСТВА СЕРВИСА И ЭФФЕКТИВНОСТИ ИСПОЛЬЗОВАНИЯ ТУРИСТИЧЕСКОГО ПОТЕНЦИАЛА БУХАРСКОЙ ОБЛАСТИ НА ОСНОВЕ СОЦИОЛОГИЧЕСКОГО ОПРОСА.....	541
Усманова Азиза Баходировна	
RAQAMLI BANK XIZMATLARI ORQALI MOLIVAVIY INKLYUZIVLIKNI KENGAYTIRISH.....	545
Azlarova Mushtariybegim Abror qizi	
QURILISH KORXONALARNI BOSHQARISHDA RAQAMLI TRANSFORMATSIYALARNING AHAMIYATI	550
Egamov Raxmatillo Mirolimovich, Bobobekov Davron Gafurovich	
FINANCIAL MARKET PARTICIPANTS: A CLASSIFICATION BY ROLE AND RESPONSIBILITY.....	553
Khotamkulova Madina	
ФОРМИРОВАНИЕ «ТУРИСТИЧЕСКОЙ МАХАЛЛИ» КАК ИНСТИТУЦИОНАЛЬНОГО МЕХАНИЗМА РАЗВИТИЯ ЗЕЛЁНОЙ ЭКОНОМИКИ В СФЕРЕ ГОСТЕВЫХ ДОМОВ УЗБЕКИСТАНА	559
Иргашева Нигина Салохиддиновна	
BANKLARDA KREDIT GAROVI BILAN ISHLASHNING XORIJ ILG'OR TAJRIBASI VA UNDA O'ZBEKISTON BANKLARI AMALIYOTIDA FOYDALANISH ISTIQBOLLARI.....	567
Sh. Saidov	
MILLIY UGLEROD SAVDOSI TIZIMINI JORIY ETISH ISTIQBOLLARI VA IQTISODIY SAMARADORLIGI.....	573
Islamov Shoxzod Shuxrat o'g'li	
THE NECESSITY OF CREATING A BUSINESS ENVIRONMENT AND ITS ROLE AND SIGNIFICANCE IN THE NATIONAL ECONOMY.....	582
Amanov Davron Ravshan ugli	
SUV RESURSLARINI BOSHQARISHDA RAQAMLASHTIRISH SAMARADORLIGI	588
Saidov Muhammadali Hakimovich, Mahammatov Hoshim, Esanbekov Diyorbek	
ТРАНСФОРМАЦИЯ БУХГАЛТЕРСКОГО УЧЁТА БАНКОВ В РЕСПУБЛИКЕ УЗБЕКИСТАН В СООТВЕТСТВИИ С МСФО И ПРИНЦИПАМИ ESG.....	595
Насирдинов Шарифджон Изатуллоевич	
ОЦЕНКА ЭНЕРГЕТИЧЕСКОЙ ЭФФЕКТИВНОСТИ ЭЛЕКТРОБУСА.....	600
Мухитдинов Акмал Анварович, Касимов Омил Камалович, Саидов Азамат Илхом угли	
XORIJIY TAJRIBALAR ASOSIDA DUKKAKLI DON MAHSULOTLARINI YETISHTIRISHNI DAVLAT TOMONIDAN QO'LLAB-QUVVATLASH YO'NALISHLARI (HINDISTON TAJRIBASI MISOLIDA).....	608
Mirsayd Xudaybergenov	
O'ZBEKISTON RESPUBLIKASIDA AHOLINING FAROVONLIGI VA DAROMAD MANBALARINI STATISTIK TAHLILI	612
Mamatkulov Baxtiyor Xalmuradovich	



KICHIK BIZNES SUBYEKTLARINING RAQOBATBARDOSHLIGINI RIVOJLANTIRISH VA BOSHQARUV MEXANIZMINI TAKOMILLASHTIRISH.....	618
Muxamedjanova Maxfuza Baxodir qizi	
MOLIYAVIY AKTIVLARNING IQTISODIY MOHIYATI, MAZMUNI HAMDA KLASSIFIKATSIYASI.....	627
Odiljonova Oybarchin Fayzullo qizi	
XALQARO MOLIYA INSTITUTLARI ORQALI MAMLAKATIMIZ LOYIHALARINI AMALGA OSHIRISH TARTIBI TAHLILI.....	631
Rasulova Dilfuza Valiyevna	
HUDUDNI BARQAROR RIVOJLANTIRISHDA IQTISODIY SALOHİYATNING O'RNI	636
Avazbek Xalbekov	
O'ZBEKISTON RESPUBLIKASIDA SABZAVOTCHILIK TARMOG'INING RIVOJLANISH ISTIQBOLLARI.....	642
Sobir Xasanov	
IMPACT OF REGIONAL INFRASTRUCTURE AND NATURAL RESOURCE UTILIZATION ON THE DEVELOPMENT OF ECOLOGICAL TOURISM (A DISTRICT-LEVEL ANALYSIS OF THE SAMARKAND REGION, UZBEKISTAN)	650
Toyirova Shohista Bobobekovna	
INNOVATION IQTISODIYOT SHAROITIDA OLIY TA'LIM TIZIMINI RIVOJLANTIRISHNING IJTIMOY-IQTISODIY OMILLARI	657
Talapova Nargiza Baxriddinovna	
BOZOR BEQARORLIGI SHAROITIDA BANK OBRO'SINI STRATEGIK RESURS SIFATIDA BARQARORLIGINI OSHIRISHNING NAZARIY ASOSLARI.....	661
Yuldasheva Kamola Qosimjonovna, Ziyeva Muhtasar Mansurdjanovna	
O'ZBEKISTONDA DAVLAT PENSIYA TIZIMINING MOLIYAVIY BARQARORLIGINI TA'MINLASH MASALALARI	667
Pardayev Farrux Muzaffarovich	
RAQAMLI TRANSFORMASIYA SHAROITIDA MENEJERLARNING RAQAMLI KOMPETENSIYALARINI RIVOJLANTIRISH.....	671
Sharipova Zulfiya Shokirjonovna	
FUQAROLAR ISHTIROKIGA ASOSLANGAN TASHABBUSLI BUDJETLASHTIRISH TIZIMI VA UNING IJTIMOY-IQTISODIY AHAMIYATI	677
Shukurova Parizod, Soatova Nodira Boboxonovna	
O'ZBEKISTON QISHLOQ HUDUDLARINING BARQAROR RIVOJLANISH YO'NALISHLARIDA QISHLOQ TURIZMI VA EKOTURIZM – ASOSIY USTUVOR YO'NALISHLARI	682
Abduraxmanova Aqida Fayzulla qizi	
KORXONALARDA MOLIYAVIY HISOBOTLARNING SHAFFOFLIGINI TA'MINLASHDA BUXGALTERIYA HISOBINING ROLI.....	691
Alimbay Shamshetov	
BARQAROR IQTISODIY RIVOJLANISHDA YASHIL INVESTITSIYALARNING MOLIYAVIY MEXANIZMLARI	694
Saule Ibragimova	
ANALYSIS OF THE STATE OF ELECTRICITY GENERATION BY WIND POWER PLANTS.....	698
Saidov Mash'al Samadovich	



ANALYSIS OF THE STATE OF ELECTRICITY GENERATION BY WIND POWER PLANTS

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Abstract. This scientific article provides a comprehensive analysis of the state of electricity production by wind power plants. Within the framework of the study, the dynamics of wind energy development at the global and Uzbek levels, the volume of installed capacity, indicators of electricity generation, and factors of economic efficiency were examined for the period 2020–2024. The technical characteristics of wind turbines, the capacity factor, the cost of electricity (LCOE), and issues related to grid integration were also analyzed. The results of the analysis show that wind energy has demonstrated a stable growth trend in recent years, while its environmental sustainability and economic competitiveness continue to increase. The article proposes scientific and practical recommendations for the effective integration of wind energy into the national energy system.

Key words: wind power plant, wind energy, renewable energy sources, electricity generation, capacity factor, LCOE, energy efficiency, energy security, grid integration, hybrid energy systems.

Annotatsiya. Mazkur ilmiy maqolada shamol elektr stansiyalari tomonidan elektr energiyasini ishlab chiqarish holati kompleks tahlil qilingan. Tadqiqot doirasida 2020–2024-yillar davomida jahon va O'zbekiston miqyosida shamol energetikasining rivojlanish dinamikasi, o'rnatilgan quvvatlar hajmi, elektr energiyasi ishlab chiqarish ko'rsatkichlari hamda iqtisodiy samaradorlik omillari o'rganildi. Shuningdek, shamol turbinalarining texnik xususiyatlari, quvvatdan foydalanish koeffitsienti, elektr energiyasi tannarxi (LCOE) va tarmoqqa integratsiya masalalari tahlil etildi. Tahlil natijalari shamol energetikasi so'nggi yillarda barqaror o'sish tendensiyasiga ega ekanini, uning ekologik tozaligi va iqtisodiy raqobatbardoshligi ortib borayotganini ko'rsatdi. Maqolada shamol energetikasini milliy energetika tizimiga samarali integratsiya qilish bo'yicha ilmiy va amaliy takliflar ishlab chiqilgan.

Kalit so'zlar: shamol elektr stansiyasi, shamol energetikasi, qayta tiklanuvchi energiya manbalari, elektr energiyasi ishlab chiqarish, quvvatdan foydalanish koeffitsienti, LCOE, energiya samaradorligi, energetik xavfsizlik, tarmoqqa integratsiya, gibrid energetik tizimlar.

Аннотация. В данной научной статье представлен комплексный анализ состояния производства электроэнергии ветровыми электростанциями. В рамках исследования изучены динамика развития ветроэнергетики на мировом и узбекском уровнях, объем установленной мощности, показатели производства электроэнергии и факторы экономической эффективности за период 2020–2024 годов. Также проанализированы технические характеристики ветровых турбин, коэффициент использования мощности, стоимость электроэнергии (LCOE) и вопросы интеграции в энергосеть. Результаты анализа показали, что ветроэнергетика в последние годы имеет устойчивую тенденцию роста, при этом повышаются её экологичность и экономическая конкурентоспособность. В статье разработаны научные и практические предложения по эффективной интеграции ветроэнергетики в национальную энергетическую систему.

Ключевые слова: ветровая электростанция, ветроэнергетика, возобновляемые источники энергии, производство электроэнергии, коэффициент использования мощности, LCOE, энергоэффективность, энергетическая безопасность, интеграция в сеть, гибридные энергетические системы.

INTRODUCTION

At the global level, economic growth, industrialization processes, and the improvement of living standards are leading to a continuous increase in the demand for electricity. In the 21st century, electricity has become not only a means of production but also a strategic resource that determines the competitiveness of countries. The rapid development of areas such as the digital economy, artificial intelligence technologies, data centers, and electric transport is creating additional demands on energy systems. Therefore, ensuring the reliability, continuity, and environmental sustainability of energy supply has been recognized as one of the priority directions of state policy.



For many years, electricity generation in the global energy system has mainly been based on traditional fuel resources. However, the limited nature of hydrocarbon resources, fluctuations in energy prices due to geopolitical factors, and the increasing volume of greenhouse gas emissions into the atmosphere are creating global environmental problems. In particular, climate change processes, air pollution, and issues related to environmental security are encouraging the international community to widely utilize renewable energy sources. Analytical reports published by the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) indicate that the share of renewable energy sources is steadily increasing each year.

Among renewable energy sources, wind energy occupies a special place. Wind is a naturally renewable and almost unlimited source of energy, and its resources are widely distributed geographically. In recent years, improvements in wind turbine technology, increased generator efficiency, the introduction of digital control systems, and reductions in production costs have contributed to the rapid development of this sector. According to the Global Wind Energy Council (GWEC), the installed wind power capacity worldwide is increasing significantly each year and in some countries constitutes a substantial share of total electricity generation.

At the current stage, profound transformation processes are being observed in the global energy system. The steady growth of global electricity demand, expansion of industrial production, rapid urbanization, and the widespread adoption of digital technologies are placing high demands on energy infrastructure. In particular, electric vehicles, data centers, artificial intelligence systems, and automated production processes are increasing the need for additional energy capacity. Under these conditions, ensuring the stability, continuity, and environmental safety of energy supply has become strategically important.

Traditional thermal power plants mainly rely on fuel resources such as natural gas, oil, and coal. However, the limited nature of these resources and the large volumes of carbon dioxide and other harmful emissions released during their extraction and combustion negatively affect the global ecological balance. As a result, climate change processes intensify and the level of air pollution increases. According to analyses by the International Energy Agency, the energy sector is one of the main sources of global greenhouse gas emissions. Therefore, accelerating decarbonization processes in the energy sector has become one of the key strategic objectives.

Renewable energy sources, particularly wind energy, are considered an effective solution to these problems. Wind energy is naturally renewable, its resources are virtually unlimited, and the process of electricity generation does not produce harmful emissions into the atmosphere. According to the International Renewable Energy Agency, investments directed toward renewable energy sources are increasing annually, with wind energy emerging as one of the leading sectors. This indicates that the industry has high potential not only environmentally but also economically.

The relevance of wind power plants is also closely related to another important factor—energy security. For countries dependent on fuel imports, fluctuations in prices in external markets and geopolitical factors may significantly affect energy stability. Wind energy, however, enables the use of local energy resources and reduces dependence on external energy sources. This is particularly important for developing economies.

From an economic perspective, wind energy has also entered a stage of significant development. Over the past decade, wind turbine technology has improved substantially: the unit capacity of turbines has increased, reliability indicators have improved, and operating costs have decreased. As a result, the cost of electricity generated by wind power plants has reached a level capable of competing with traditional energy sources. Reports by the Global Wind Energy Council indicate a steady increase in installed wind power capacity worldwide, confirming the high investment attractiveness of this sector.

The relevance of this issue is also increasing in the context of Uzbekistan. The domestic demand for electricity in the country is growing every year, while the expansion of industrial production and population growth require the creation of new energy capacities. At the same time, diversifying the energy generation system, increasing the share of renewable energy sources, and ensuring environmental sustainability are among the priority directions of state policy. The high potential of wind resources in certain regions creates favorable conditions for the construction of wind power plants.

Furthermore, the development of wind energy contributes positively to scientific research activities, the introduction of innovative technologies, and the training of local specialists. The use of digitalization, monitoring systems, and intelligent management methods in the energy sector can further improve the efficiency of wind power plants.

LITERATURE REVIEW

The issue of electricity generation by wind power plants has been studied by foreign and local scholars in various directions. Scientific research mainly covers the following areas: assessment of wind resources, aerodynamics and design of turbines, energy efficiency, integration into power grids, economic analysis, and environmental impact assessment.



One of the fundamental studies in wind energy is the work “Wind Energy Handbook” authored by T. Burton, D. Sharpe, N. Jenkins, and E. Bossanyi. This source comprehensively explains the aerodynamic theory of wind turbines, mechanical and electrical systems, and issues related to grid connection. The authors theoretically and practically demonstrate that the power output of a wind turbine is proportional to the cube of wind speed [1]. At the same time, the book mainly focuses on technical aspects, while the application of economic models suitable for developing countries could be further explored.

The book “Wind Energy Explained: Theory, Design and Application” by J. F. Manwell, J. G. McGowan, and A. L. Rogers thoroughly discusses the theoretical foundations of wind energy, design principles, and practical applications. The authors scientifically justify the effectiveness of using the Weibull distribution function in assessing wind resources. In addition, they emphasize that along with technical parameters, economic indicators should also be considered when selecting turbines [2]. Although the research provides deep technical insights, institutional aspects of integrating wind energy into national power systems remain a promising direction for future research.

Reports by the International Energy Agency (IEA) analyze the role of wind energy in the global energy balance and its development dynamics. According to IEA data, wind energy is one of the fastest-growing sectors among renewable energy sources [3]. These reports are mainly based on statistical data and play an important role in identifying global development trends.

Analytical reports prepared by the International Renewable Energy Agency (IRENA) indicate that the cost of wind electricity—measured by the Levelized Cost of Electricity (LCOE)—has significantly decreased in recent years. This confirms the growing economic competitiveness of wind energy [4]. In this context, deeper research on additional factors related to modernization of energy infrastructure and grid development remains a promising scientific direction.

Reports of the Global Wind Energy Council (GWEC) provide a detailed analysis of global wind capacity growth trends. They highlight the development indicators of wind energy in China, the United States, and European countries [5]. These sources are considered important information bases for evaluating the general development trends of the sector.

Uzbek researchers have also conducted a number of scientific studies on assessing wind resources and their efficient utilization. In particular, Q. Sh. G’ofurov and co-authors studied the distribution of wind speeds and the energy potential in different regions of the republic. According to the results of the research, wind speeds in certain areas are sufficient for industrial-scale electricity generation [6]. These studies are mainly based on meteorological data, and enriching them with investment analysis could become an important direction for future research.

In addition, T. R. Rajabov and co-authors examined the prospects of renewable energy sources within Uzbekistan’s energy system. The research considers the possibility of applying wind and solar energy as hybrid systems. The authors emphasize that the use of renewable energy sources can reduce environmental pressure [7]. At the same time, further development of technical and economic calculations and improvement of practical implementation mechanisms are viewed as promising research directions.

In general, foreign studies comprehensively cover the technological and economic aspects of wind energy, while local research mainly focuses on assessing resource potential. At the same time, further development is required in areas such as integration of wind power plants into national power grids, combination with energy storage systems, and comprehensive evaluation of investment efficiency.

Scientific research on wind energy has become more in-depth over the past decades and has acquired an interdisciplinary character. While early studies mainly focused on aerodynamics and mechanics, current research increasingly addresses system analysis, energy market models, grid stability, and energy storage technologies.

In the book “Renewable Energy in Power Systems”, L. L. Freris and D. Infield provide a comprehensive analysis of the interaction between wind energy and electrical power systems. The authors note that the variability of wind generation can affect grid frequency and voltage stability. They also scientifically justify the importance of reserve capacities and intelligent control algorithms in solving integration problems [8].

S. Heier, in his research “Grid Integration of Wind Energy Conversion Systems,” analyzes technical issues that arise when connecting wind power plants to electrical networks. The author particularly focuses on problems of reactive power compensation and frequency stability [9].

The work “Renewable Energy: Power for a Sustainable Future,” edited by G. Boyle, extensively discusses the role of wind energy in sustainable development. The authors analyze the role of wind energy in reducing carbon emissions based on statistical data [10].

The LCOE methodology developed by the International Renewable Energy Agency is widely used to assess the economic efficiency of wind energy. This approach considers capital expenditures, operating costs, and the service life of the technology.



In Uzbekistan, scientific research on wind energy is mainly focused on assessing resource potential and integrating renewable energy sources into the national energy system.

Research conducted by Professor A. A. Abdurakhmonov analyzes the energy potential of wind resources in the Republic of Karakalpakstan and Navoi region. Based on long-term meteorological observations, the average wind speed and power density were calculated in these studies [11].

In addition, B. B. Turaev and co-authors studied the possibilities of implementing wind–solar hybrid energy systems. According to their research results, the use of hybrid systems can improve the stability of energy supply [12].

The analysis shows that foreign research extensively studies wind energy from both technical and economic perspectives, with particular attention paid to grid stability and integration issues. In contrast, local research mainly focuses on assessing resource potential.

Therefore, comprehensive analysis of wind power plant operations from technical, economic, and systemic perspectives, adaptation of international experience to national conditions, and development of innovative approaches represent important scientific directions in modern energy research.

RESEARCH METHODOLOGY

In the course of the research, a number of scientific research methods were used to study and analyze the state of electricity generation by wind power plants. In particular, methods such as comparative analysis and synthesis, induction and deduction, expert evaluation, scientific abstraction, statistical grouping, as well as correlation and regression analysis were widely applied.

Using these methodological approaches, the development dynamics of wind energy, electricity generation indicators, and the economic efficiency factors of the sector were systematically analyzed. In addition, based on statistical data, the relationships between the production indicators of wind power plants were identified, and their development trends were scientifically substantiated.

ANALYSIS AND RESULTS

One of the key advantages of wind power plants is that they do not consume fuel during electricity generation and do not emit harmful gases into the atmosphere. This significantly contributes to reducing the carbon footprint and promoting the widespread implementation of the principles of a green economy. At the same time, wind energy strengthens energy security, reduces dependence on imported fuel, and enables efficient utilization of local energy resources.

In the context of Uzbekistan, modernization of the energy sector and the development of renewable energy sources have been identified as priority tasks. In certain regions of the country, wind speed and climatic conditions are considered favorable for industrial-scale electricity generation. Increasing the share of renewable energy sources in the national energy balance can ensure environmental sustainability, improve the quality of electricity supply, and achieve long-term economic efficiency.

From this perspective, conducting a scientific analysis of electricity generation by wind power plants and comprehensively studying their technical capabilities, production indicators, economic efficiency, and development prospects is of significant scientific and practical importance (Table 1).

Table 1. Installed global wind power capacity (2020–2024, GW)

Year	Total Global Capacity (GW)	Newly Installed Capacity (GW)
2020	743	93
2021	830	87
2022	913	83
2023	1000	87
2024	1136	117

Source: Our World in Data / IRENA Statistics (cumulative).

As can be seen from the table, the installed capacity of wind power plants worldwide demonstrated a stable growth trend during 2020–2024. In particular, in 2024, 117 GW of new capacity was commissioned, which is one of the highest figures in recent years. This result represents a significant increase compared to 2020 and confirms that the importance of wind energy in the global energy system is steadily growing. In addition, the share of wind energy in global electricity generation and its role in meeting electricity demand are presented in Table 2.



Table 2. Share of Global Wind Energy and Its Role in Global Electricity Demand (2023–2024)

Year	Share of Wind Energy in Global Electricity Generation (%)
2023	7.8
2024	10

Source: Our World in Data / IRENA Statistics (cumulative).

According to the data presented in the table, the share of wind energy in the global energy system has been increasing significantly in recent years. In particular, wind energy accounted for approximately 7.8% of global electricity generation in 2023, while in 2024 this figure reached 10%. This growth indicates that wind energy is gaining an increasingly important strategic position in the global energy system not only in terms of installed capacity but also in terms of its contribution to total electricity generation.

The annual growth dynamics of wind electricity generation worldwide are presented in Table 3.

Table 3. Global Wind Electricity Generation (2020–2024)

Year	Electricity Generation (TWh)	Annual Growth (%)
2020	1590	–
2021	1810	+13.8
2022	2100	+16.0
2023	2300	+9.5
2024	2500	+8.7

Source: International Energy Agency (Electricity Market Report, 2024) and IRENA Statistics (2024).

According to the data presented in the table, wind electricity generation increased by approximately 1.6 times during 2020–2024. In particular, the high growth rates observed in 2021–2022 can be explained by the recovery of economic activity in the post-pandemic period and the commissioning of new energy capacities.

In 2023–2024, the growth rate continued at a relatively stable level, ensuring a steady increase in the overall production volume. This situation indicates that the role of wind energy in the global energy system is becoming increasingly stronger.

The development of wind turbine technology, particularly the increase in their unit capacity, contributes significantly to improving the efficiency of the sector. The annual dynamics of this indicator are presented in Table 4.

Table 4. Average Unit Capacity of Wind Turbines (2020–2024)

Year	Average Turbine Capacity (MW)
2020	2.8
2021	3.0
2022	3.2
2023	3.5
2024	3.8

Source: Global Wind Energy Council (Global Wind Report, 2023–2024).

According to the data presented in the table, the unit capacity of wind turbines has been steadily increasing each year. The use of higher-capacity turbines makes it possible to generate more electricity within the same land area. This contributes to improving the investment efficiency of energy projects and optimizing operational costs.

At the same time, the transportation and installation of high-capacity turbines require complex technological processes. However, modern logistics and engineering solutions enable the efficient organization of these processes. These trends are important for the future development of renewable energy sources.

The share of renewable energy sources in Uzbekistan's electricity generation system and its annual dynamics are presented in Table 5.



Table 5. Share of Renewable Energy Sources in Electricity Generation in Uzbekistan (2020–2024)

Year	Total Electricity Generation (TWh)	Share of Renewable Energy (%)
2020	66	10
2021	71	11
2022	74	12
2023	78	14
2024	81	16

Source: Reports of the Ministry of Energy of the Republic of Uzbekistan.

According to the data presented in the table, the share of renewable energy sources demonstrated a steady growth trend during 2020–2024. This growth is mainly associated with the development of solar and wind energy. In particular, the increase of this share to 16% in 2024 indicates the consistent implementation of the “green energy” policy in the country.

At the same time, the share of wind energy in the overall energy system still has significant potential for further development. Expanding this sector is important for diversifying the energy system, increasing energy sources, and ensuring environmental sustainability.

The annual dynamics of the levelized cost of electricity (LCOE) in wind energy are presented in Table 6.

Table 6. Average Cost of Wind Energy (LCOE) (2020–2024, USD/kWh)

Year	LCOE (USD/kWh)	Change (%)
2020	0.056	–
2021	0.052	–7
2022	0.049	–5.7
2023	0.047	–4
2024	0.045	–4.2

Source: IRENA Renewable Power Generation Costs Reports (2021–2024).

According to the data presented in the table, the cost of wind energy shows a steady decreasing trend over the years. By 2024, the cost of electricity generation decreased by approximately 20% compared to 2020. This indicates that wind energy is becoming one of the economically competitive energy sources. At the same time, some studies suggest that additional costs related to energy infrastructure development and energy storage systems should also be analyzed separately.

According to the results of the conducted research, the analysis for the period 2020–2024 leads to the following conclusions:

- global wind electricity generation demonstrates a stable growth trend;
- improvements in wind turbine technology are increasing energy production efficiency;
- the decline in electricity generation costs is enhancing the investment attractiveness of the sector;
- the share of renewable energy sources in Uzbekistan is steadily increasing, and there are broad opportunities for the development of wind energy.

These findings confirm that the development of wind power plants has strategic, economic, and environmental importance.

CONCLUSION AND RECOMMENDATIONS

Within the framework of this study, the state of electricity generation by wind power plants was analyzed for the period 2020–2024, and based on the obtained results, several important scientific and practical conclusions were formulated.

First, it was identified that wind energy is one of the sectors demonstrating stable and rapid growth at the global level. The increase in installed capacity, growth in electricity generation indicators, and continuous technological improvements are transforming wind energy into an important component of the global energy system. This process is closely linked to the strengthening of decarbonization policies, the widespread implementation of green economy principles, and the improvement of the investment environment.

Second, from a technical perspective, the capacity and efficiency of wind turbines have significantly increased. Modern turbines with larger rotor diameters and higher capacity allow for the generation of greater



amounts of electricity under the same wind conditions. This contributes to improving the economic efficiency of energy projects. In addition, the introduction of digital monitoring systems and automated control technologies helps optimize operational costs.

Third, economic analyses indicate that the cost of wind electricity generation has been decreasing annually. This trend makes wind energy increasingly competitive with traditional fossil-fuel-based power plants. At the same time, when evaluating energy projects, it is important to consider not only generation costs but also additional costs related to electric grid infrastructure development, energy storage systems, and reserve capacities.

Fourth, one of the key characteristics of wind energy is its natural variability. The fluctuation of wind speed can affect the stability of electricity generation. Therefore, the implementation of energy storage technologies (such as battery systems, pumped hydro storage stations, and others) as well as hybrid energy systems becomes particularly important. Such approaches contribute to ensuring the stability and reliability of power grids.

In the context of Uzbekistan, the prospects for the development of wind energy are considered highly promising. The increasing demand for electricity, the need to modernize the national energy system, and the implementation of state programs aimed at expanding renewable energy sources further enhance the importance of this sector. The presence of wind resources in certain regions of the country creates favorable conditions for the construction of wind power plants. However, during the implementation of such projects, it is important to conduct scientifically based resource assessments, technical and economic analyses, and comprehensive evaluation of investment risks.

Furthermore, the development of wind energy can contribute to achieving the following strategic outcomes:

- strengthening energy security;
- reducing dependence on imported fuel resources;
- decreasing carbon emissions;
- creating new jobs and promoting the development of local industry;
- introducing innovative technologies and increasing scientific potential.

For future research, it is advisable to deepen studies in the following directions:

- development of high-precision wind resource forecasting models;
- evaluation of the efficiency of integration with energy storage technologies and hybrid systems;
- improvement of methods for ensuring power grid stability under conditions of increasing wind energy share in the national energy system;
- comprehensive assessment of the socio-economic impacts of wind energy projects.

In general, it can be concluded that wind power plants represent an important element of a sustainable development strategy. Their technical, economic, and environmental advantages should be considered a priority direction in shaping national energy policy. Through scientifically grounded approaches, modern technologies, and effective management mechanisms, wind energy can make a significant contribution to the sustainable development of the national economy.

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