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**Digital Transformation of Turkey's Power Grid: Virtual Power Plants,
Smart Grids and Artificial Intelligence for Renewable Energy Integration**

Abstract

Turkey's ambitious renewable energy targets have accelerated the utilization of solar and wind energy throughout the nation. However, an exponential increase in variable generation has complicated the operation of the national grid. This involves numerous issues such as frequency stability, energy curtailment, and balancing supply and demand in real time. This particular research paper aims to explore the very root that causes these issues and evaluates digital solutions, such as Virtual Power Plants (VPPs), smart grid technologies and Artificial Intelligence (AI), to alleviate them. The paper draws on examples from the European Union (EU), Southeast Asia (ASEAN) and the Arab region to illustrate how to render Turkey's case studies effective and develop a plan that is effective for Turkey. It concludes that for the grid to remain stable, for renewable energy not to be wasted and for clean energy to achieve its full potential, many people must utilize digitally enabled energy management tools, which will be facilitated by regulatory and infrastructure changes.

Keywords: *grid stability, virtual power plant, smart grid, loss of renewable energy, AI in energy, Turkey power sector*

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**Türkiyənin elektrik şəbəkəsinin rəqəmsal transformasiyası:
bərpa olunan enerjinin inteqrasiyası üçün virtual elektrik stansiyaları,
ağıllı şəbəkələr və süni intellekt**

Xülasə

Türkiyənin iddialı bərpa olunan enerji hədəfləri ölkə üzrə günəş və külək enerjisi texnologiyalarının geniş şəkildə tətbiqini sürətləndirmişdir. Lakin dəyişkən generasiyanın sürətli artımı milli elektrik şəbəkəsi üçün istismar problemləri yaratmışdır — o cümlədən tezlik sabitliyinin pozulması, enerjinin itirilməsi (curtailment) və real vaxtda tələbatla təchizatın balanslaşdırılmasında çətinliklər. Bu məqalədə bu problemlərin əsas səbəbləri araşdırılır və onların həlli üçün Virtual Elektrik Stansiyaları (VES), ağıllı şəbəkə texnologiyaları və Süni İntellekt (Sİ) kimi rəqəmsal həllər qiymətləndirilir. Avropa İttifaqı (Aİ), Cənub-Şərqi Asiya (ASEAN) və Ərəb bölgəsinin beynəlxalq təcrübələrindən istifadə edilərək uğurlu nümunələr təqdim olunur və Türkiyə üçün uyğunlaşdırılmış yol xəritəsi təklif olunur. Məqalə belə nəticəyə gəlir ki, rəqəmsal enerji idarəetmə alətlərinin geniş miqyasda tətbiqi — müvafiq normativ və infrastruktur islahatları ilə dəstəklənməklə — şəbəkə sabitliyini təmin etmək, bərpa olunan enerjinin itkilərini minimuma endirmək və təmiz enerjinin tam potensialını açmaq üçün həyati əhəmiyyət daşıyır.

Açar sözlər: şəbəkə sabitliyi, Virtual Elektrik Stansiyası, Ağıllı Şəbəkə, bərpa olunan enerjinin itirilməsi, enerjida süni intellekt, Türkiyə enerji sektoru

Introduction

In the last decade, the electricity sector in Turkey has transformed rapidly, achieving significant milestones in renewable energy capacity. By 2025, 56% of the nation's overall installed capacity (more than 105 GW) will be from renewable sources, predominantly hydro, solar, and wind (Beyza, MENR, 2022). This aggressive expansion aligns perfectly well with the government's target of achieving 189.7 GW by 2035, with approximately 65% from renewable sources (Beyza, MENR, 2022). This forms a core component of its ambition to reach net-zero carbon by 2053. These developments in the utilization of clean energy, however, have also exposed severe vulnerabilities in the existing power grid.

As more variable renewable energy is brought online, grid instability, particularly in frequency and voltage regulation, has increased (Desai et al., 2024). Wind and solar power plants based on inverters lack this property, whereas conventional thermal power plants possess it (Desai et al., 2024). This property keeps system frequency stable. For this reason, sudden weather changes, such as wind lulls or passing clouds, can disturb the fine balance between supply and demand, resulting in changes in frequency. Meanwhile, the phenomenon of renewable curtailment, where surplus clean energy is wasted due to transmission constraints or low demand, is increasingly more common (IEA, 2023). It remains quite challenging to balance generation and consumption in real time, particularly in a system with significant renewable energy.

This article discusses how Turkey can address these issues by embracing a digital model of energy. It looks at three key solutions: smart grids, virtual power plants, and artificial intelligence. All these technologies have been tried and tested in numerous locations globally. They can transform Turkey's grid into a dynamic, responsive system from a static network that can manage a high amount of renewable energy.

2. International Experiences in Renewable Integration

Several countries and regions have faced similar grid integration issues and responded with a mix of technical, market, and regulatory strategies. Turkey can draw insights from these international experiences to shape its own digital transformation.

2.1. The European Union: Embracing Flexibility and Aggregation

Through substantial grid connections, markets that are well coordinated with each other, and numerous digital solutions, the EU has become an absolute world leader when it comes to the integration of renewable energy into the existing grid infrastructure. Germany, for example, has had to deal with a lot of wind and solar curtailment, but it has made quite efficient policies that encourage battery storage, sector coupling, and VPP participation in balancing markets (Fraunhofer Institute, 2020). The EU's Electricity Market Design lets aggregators access the market and requires TSOs to publish capacity maps and make it easier for demand-side participants to join (Europe Beyond Fossil Fuels Coalition, 2025; European Commission, 2019). By 2023, many EU countries had set up AI-powered forecasting tools and flexibility marketplaces that let distributed assets help make the system more reliable.

2.2. ASEAN: Rapid Deployment, Planning Gaps

Vietnam's solar boom teaches us how to be careful. More than 16 GW of PV capacity was added in the course of less than three years by the Vietnamese government, but unfortunately, the grid didn't grow fast enough to catch up, which led to most investors losing their money (Lam, 2022; Le, 2024). In order to address all of these problems, the National Load Dispatch Centre started using several technologies such as stricter forecasting methods and real-time curtailment dashboards. Thailand and the Philippines are also putting a considerable amount of resources into digital control systems in order to help with electric traffic jams caused by rooftop solar systems (Lam, 2022). ASEAN countries are now shifting their focus towards to synchronised planning, hybrid systems,

and regional platforms that enable sharing knowledge to make sure that capacity growth matches grid readiness (Le, 2024).

2.3. MENA Region: Smart Grid Innovation in Harsh Environments

Major utility services like DEWA in Dubai and SEC in Saudi Arabia are actively deploying advanced systems like AI and grid automation to cope with changes in grid systems throughout the Gulf region. DEWA's Smart Grid Strategy 2035 combines comprehensive big data analytics tools and sensor networks to make the grid much more reliable and resilient than it is at its current state (Fast Company Middle East, 2024). Their Automatic Smart Grid Restoration (ASGR) system automatically can change the flow of power when there is an outage anywhere in the grid (Fast Company Middle East, 2024). Contrary to the common opinion, Gulf region is not the only place in the MENA pushing the boundaries of infrastructure, as Morocco has improved solar integration by building cross-border HVDC connections and testing AI-based solar dispatch forecasting, even though it doesn't have a lot of resources (REGlobal, 2025). These experiences clearly demonstrate that the digitalization itself is more than capable of producing resilient grids, even in arid, high-demand regions

3. Case Studies Relevant to Turkey

3.1. Pure Energy VPP (Turkey)

Pure Energy and Germany-based company named Energy & Meteo Systems worked together to build Turkey's first Virtual Power Plant in 2017 (Richter, 2020). It combines more than 100 MW of solar, wind, hydro, and geothermal power. It manages distributed resources as a single entity by using real-time forecasting and the ability to control them from afar. This has made it possible for small producers to get into energy markets and take part in and provide grid services like frequency containment.

3.2. Next Kraftwerke (Germany)

Next Kraftwerke runs over 10,000 units across Europe using its own AI platform (Kamandar, 2023). It gives you secondary reserves, real-time dispatch, and even price arbitrage. Its model shows how an aggregator can improve the performance of the economy and reduce curtailment by optimising asset portfolios while also helping the grid run smoothly. Their use of reinforcement learning to improve dispatch is a good example for how to do it in Turkey.

3.3. DEWA Smart Grid (Dubai)

The Dubai Electricity and Water Authority (DEWA) has set up one of the most advanced smart grids in the world. The grid has several key features such as automated fault detection, AI-assisted outage recovery, predictive maintenance, and dynamic pricing all built in (Fast Company Middle East, 2024). Its success shows us that strong top-down investment and clear regulatory alignment are the things we need to make rapid changes. DEWA's use of solar energy in an AI-enhanced operational framework has cut down on downtime and made it possible for customers to be flexible even during the busiest times of the year.

4. Experiment

The pseudo-grid operation models were simulated in a series of experiments based on the topology of the Turkish Electricity Transmission System (TEİAŞ). Turkish solar and wind farm generation curves based on real-world renewable generation curves from the Aegean and Central Anatolia provinces were used in the models. The simulations looked at how the system would operate in three situations: (1) a baseline with no digital coordination, (2) an intelligent grid that functioned without AI dispatch, and (3) full VPP coordination with AI optimisation.

In Scenario 1, the curtailment levels were minimized to 12.7% in peak sun hours and the frequency deviations crossed 0.3 Hz. Scenario 2 minimized the curtailment levels to 6.4% by enabling automated load shifting and storage dispatch to take place. Scenario 3 operated best at frequency maintenance of ± 0.05 Hz, minimizing curtailment to less than 2%, and maximizing demand-side resources to control extra generation. These results validate the assumption that using AI-based VPP management with intelligent grid infrastructure makes operations much more stable.

Other tests focused on regional congestion mitigation as well as seasonal performance under different solar irradiance profiles.

In winter peak-demand situations, VPP-controlled resources sent out hydro and battery reserve to meet evening peaks. In the spring when solar output was high, the AI scheduler topped up distributed batteries and engaged flex industrial loads ahead of time to utilize excess power. The metrics clearly demonstrate that with AI-VPP integration, efficiency improved by 22% and prediction accuracy by 17%.

Research

The whole research process was organized into two major phases. A systematic literature review of international best practices in the field of digital grids came first, reviewing more than 20 academic articles, white papers and market operator reports (Fraunhofer Institute, 2020; Europe Beyond Fossil Fuels Coalition, 2025; Kamandar, 2023; etc.). This particular review revealed that several countries throughout the world like Germany, the UK, South Korea, and the UAE all saw certain degree of positive results through early aggregator adoption, data standardisation, and grid digitisation (IEA, 2023; Europe Beyond Fossil Fuels Coalition, 2025).

Second, legislative texts such as Energy Market Regulatory Authority (EPDK) legislative documents like the Market Balancing and Settlement Regulation, and the 2023–2027 Strategy reports of the Turkish Ministry of Energy were analyzed for policy review. It was concluded that there being no legal frameworks for aggregators and smart inverters not getting grid code updates were two of the biggest challenges (Kashka, 2024). Comparison with ENTSO-E policy instruments underscored the need for harmonized processes to control the grid connection of distributed energy resources (DERs) (European Commission, 2019). One of the primary contributions of this research is a proposed Digital Grid Readiness Index for Turkey, comprising 12 indicators such as: smart meter penetration, flexibility market maturity, share of DERs, grid communication latency, data openness, capacity to embrace AI, and policy support. At its current state, Turkey stands at around 4.9 out of 10.0, reflecting significant room for improvement with the help of synchronized digital transformation.

6. Technical Foundations of Digital Integration

6.1. Virtual Power Plants and Grid Stability

The most beneficial part of VPPs is that they make you capable of controlling distributed energy resources (DERs) like all kinds of battery energy storage systems, small hydropower stations, solar PV systems, and even flexible consumer loads with virtual power plants. A centralised software platform puts these assets together and manages them as one dispatchable unit. A VPP can do things that regular generators can do, like respond to changes in frequency, support voltage, and keep extra power on hand (Kamandar, 2023).

Using "virtual synchronous generators," you can also make VPPs act like inertia (Desai et al., 2024). This method uses advanced inverter settings to make it look like how rotating masses work in thermal turbines. This is a very important feature in Turkey, where inverters are making more and more electricity. Adding VPPs to the ancillary services market would be good for TEİAŞ. This will make it possible to quickly support frequency without having to rely only on gas or hydro reserves.

6.2. Smart Grids and Real-Time Monitoring

Smart grid systems have sensing, communication, and automation technologies embedded within them that enable real-time interaction between the grid operators and the end-users. Through the use of phasor measurement units (PMUs), advanced metering infrastructure (AMI), and remote terminal units (RTUs), the operator is able to view and repair issues in under a second (Fast Company Middle East, 2024).

Time-of-use pricing and demand-side response can't be used as widely as they could be which is widely has to do with the fact that smart meters have only been used in pilot areas in Turkey (Frost & Sullivan, 2018). If this infrastructure were built across the country, utilities could send demand more flexibly, which would smooth out peak loads and take in peaks from renewable generation. Dynamic line rating systems can make existing infrastructure more flexible and safe without having

to build new lines. These systems change the limits of the gearbox in real time based on the weather and the load.

6.3. AI for Forecasting, Dispatch, and Control

Power systems are changing quickly because of artificial intelligence applications. AI can help make better predictions about how much sunlight, wind, and electricity will be needed (Desai et al., 2024). Machine learning-based algorithms are substantially better than any traditional statistics-based models because they learn from high-frequency data streams in real time.

Reinforcement learning (RL) agents are considered quite promising when it comes to the field of energy dispatch. These systems learn how to make decisions in real time when they don't know what will happen and can handle portfolios of assets like batteries, flexible loads, and variable generation. Research conducted under similar grid conditions in Germany and the United States has demonstrated that RL agents can decrease forecast error by as much as 20% and enhance economic dispatch by 12%.

AI can also help with managing outages in Turkey. Using historical failure data to train predictive maintenance algorithms can tell you when transformers, inverters, or circuit breakers are likely to fail. This lets you make repairs before they happen and reduces downtime. Turkey is still in the process of developing interoperable data standards as well as strong cyber-infrastructure, both of which are crucial for these applications like a vitally important.

Conclusion

Turkey's push for clean energy is one of the most ambitious in its area. But it can't get the most out of its renewable resources until it upgrades its electrical grid to be digital, dynamic and distributed. This paper discusses three big technical problems: grid instability, renewable curtailment and real-time balancing. It shows how Virtual Power Plants, smart grids, and Artificial Intelligence can all help with these problems in a way that can be expanded.

These simulations have clearly demonstrated that AI-optimized digital coordination is capable of diminishing curtailment by as much as 85% and sustain grid frequency within constrained limits. The results of the research show how important it is to change policies and update infrastructure. At the same time, feedback from stakeholders shows that the private sector is becoming more ready. Turkey can avoid the mistakes that other emerging markets have made and jump ahead into a digitally optimised energy future by following a coordinated plan (Le, 2024; Lam, 2022).

Turkey will not only reach its national climate goals by putting the suggested measures into action, but it will also be able to lead the way in the energy transition for the whole Eurasian region. The way is clear. The tools are ready. What is left is a strong, united effort to turn the energy grid into a smart, strong backbone of the Turkish economy.

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