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Assessment of multi-source electricity production regulation in Türkiye based on capacity constraints and realizations

Türkiye'de birden çok kaynaklı elektrik üretim mevzuatının kapasite kısıtları ve gerçekleşmeler bazında değerlendirilmesi

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Assessment of Multi-Source Electricity Production Regulation in Türkiye Based on Capacity Constraints and Realizations

Highlights

- *6.4% of the maximum allowable capacity for auxiliary sources were allocated and granted on licenses.*
- *WEPP + SEPP hybrid system configuration accounts for 65% of the total capacity allocations.*
- *34.7% of the allocable capacities for primary sources that are not wind or solar have been realized.*
- *No hybrid energy systems of the co-firing or supporting-source form are implemented.*
- *Hybrid system options with floating solar and battery storage should be enhanced.*

Graphical Abstract

The impact of capacity allocation methodologies for multi-source electricity production systems in Türkiye is determined by comparing the allowable capacities to the actual data.

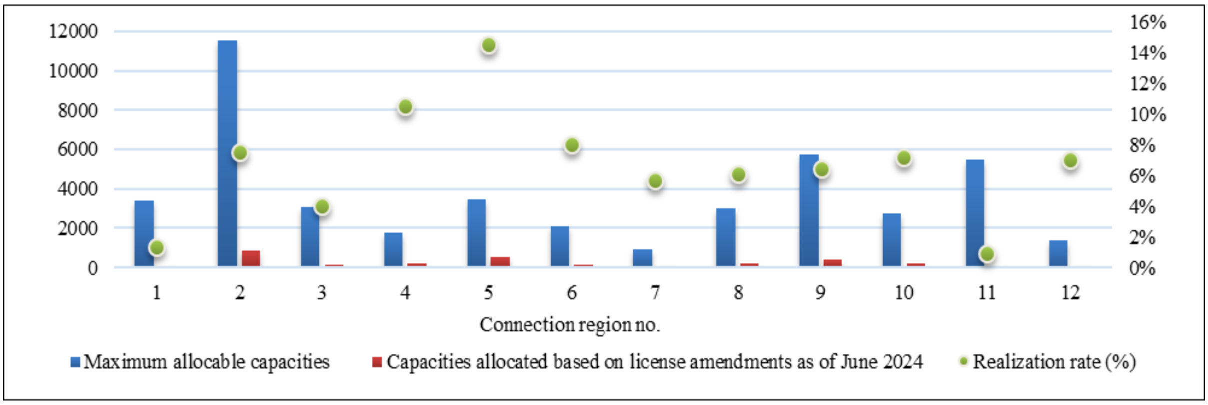

Figure. Comparison of the maximum capacities and actual capacities allocated for auxiliary sources.

Aim

Evaluating the impact of the hybrid electricity production regulation in Türkiye through the examination of the allowable capacities and realizations.

Design & Methodology

The regulation of hybrid electricity production systems is examined with a particular emphasis on capacity constraints. Data required for realizations has been gathered from the license database of EMRA as of June 13, 2024, and the results have been compared.

Originality

A thorough examination of the hybrid electricity production regulation in Türkiye, an assessment of the realizations by comparing them to the maximum allowable capacities based on connection regions and resource types, and the presentation of a variety of policy recommendations.

Findings

6.4% of the maximum installed capacity of the auxiliary sources have been realized as of June 2024. WEPP+SEPP hybrid system configuration is the most frequently chosen alternative by the investors.

Conclusion

The capacity allocation mechanism for the HEPP, BEPP, GEPP, and TPP type primary sources, as well as the legal permission procedures, must be facilitated, and additional connection capacities must be declared to boost the investments in the hybrid energy systems.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Assessment of Multi-Source Electricity Production Regulation in Türkiye Based on Capacity Constraints and Realizations

Araştırma Makalesi / Research Article

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ABSTRACT

Multi-source electricity production systems, which are inventive energy technologies utilizing the same grid infrastructure and power plant site, enable the integration of multiple resources within a single power plant. They enhance grid stability by promoting more sustainable and flexible electricity production, in addition to reducing system costs. The capacity allocation procedure for these systems is challenging in Türkiye because of the limited allowable capacities. The present study offers a comprehensive examination of the regulation of hybrid electricity production in the Turkish electricity market, with a particular focus on the mechanisms for capacity allocation in relation to a variety of primary and secondary source types. The Energy Market Regulatory Authority (EMRA) database was utilized to compile data on licensed projects and realizations. According to the findings, license amendment of 6.4% of the maximum allocable capacity in twelve connection regions was completed. Likewise, 34.7% of the allocable capacity was granted for hybrid systems that have primary sources that are not based on wind or solar, but have an auxiliary source that is based on wind or solar. The Wind+Solar PV hybrid system has the highest capacity allocations.

Keywords: Hybrid energy system, multi-source electricity production, electricity market regulation.

Türkiye'de Birden Çok Kaynaklı Elektrik Üretim Mevzuatının Kapasite Kısıtları ve Gerçekleşmeler Bazında Değerlendirilmesi

ÖZ

Aynı şebeke altyapısını ve santral sahasını kullanan, yaratıcı enerji teknolojileri olan birden çok kaynaklı elektrik üretim sistemleri, birden fazla enerji kaynağının tek bir santralde kullanılmasını sağlar. Sistem maliyetlerini düşürmenin yanı sıra daha sürdürülebilir ve esnek elektrik üretimini teşvik ederek şebeke kararlılığını artırır. Türkiye'de bu sistemlere yönelik kapasite tahsis prosedürü tahsis edilebilir kapasitelerin sınırlı olması nedeniyle zorludur. Bu çalışma, çeşitli ana ve yardımcı kaynak türlerine ilişkin kapasite tahsis mekanizmalarına odaklanarak Türkiye elektrik piyasasında hibrit elektrik üretimine ilişkin düzenlemelerin kapsamlı bir incelemesini sunmaktadır. Lisans verilen proje ve gerçekleşmelere ilişkin verilerin derlenmesinde Enerji Piyasası Düzenleme Kurumu (EPDK) veri tabanından yararlanılmıştır. Elde edilen bulgulara göre, on iki bağlantı bölgesindeki toplam azami yardımcı kaynak kapasitesinin %6,4'ünün lisans tadili tamamlanmıştır. Benzer şekilde, ana kaynağı rüzgar veya güneşe dayalı olmayıp, yardımcı kaynağı rüzgar veya güneşe dayalı olan hibrit sistemlere mevcut kapasitenin %34,7'si tahsis edilmiştir. En fazla kapasitenin tahsis edildiği hibrit sistem konfigürasyonunun ise Rüzgar+FV Güneş şeklinde olduğu görülmüştür.

Anahtar Kelimeler: Hibrit enerji sistemi, birden çok kaynaklı elektrik üretimi, elektrik piyasası mevzuatı.

1. INTRODUCTION

The majority of the world's energy demand is met by conventional energy resources, including coal, natural gas, and petroleum products. These are fossil resources with exhaustible characteristics that lead to environmental pollution due to the hazardous greenhouse gas emissions. In response to the oil crisis of the 1970s, countries began to employ renewable energy sources to satisfy their energy requirements. The process has resulted in the widespread adoption of renewable energy sources, including hydroelectricity, wind, solar, biomass, and geothermal, which are now competitive with conventional energy sources on a global scale [1]. The utilization of renewable energy sources in electricity generation is increasing on a global level, as it is a sustainable and natural source of electricity generation. The quantity of new renewable capacity additions has attained a record high in 2023, with a 50% increase from the previous year. Furthermore, it is projected that the global renewable power capacity will increase to 7300 GW during the 2023-2028 period, with solar PV and

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onshore wind contributing 95% of the total capacity expansions [2].

In addition to the substantial benefits of renewable energy sources, the intermittent nature of wind, solar PV, or hydroelectric resources, the fact that electricity production can only be conducted from solar and wind at specific times of the day, and the seasonal dependence of electricity production by means of these energy sources may pose a risk in terms of meeting the electricity demand when needed. This is primarily a concern for off-grid/stand-alone energy production systems or for remote areas in which the grid connection is relatively difficult to access. This necessitates the development and implementation of various technologies for the combined utilization of renewable energy resource types. Hybridization of individual energy resources enables more accurate projections of electricity production from wind, solar PV, or run-of-the-river hydroelectric sources, as well as the more effective management of supply and demand [3].

Energy systems that utilize multiple resources or components simultaneously in the same electricity production facility are referred to as hybrid energy systems, hybrid power systems, or hybrid renewable energy systems (HRES). One of the resources is typically fossil-based (e.g., a diesel generator, a coal or gas-fired unit), while multiple renewable energy resources may also be used in conjunction. This arrangement improves the efficiency of electricity production and the reliability of the electricity supply, and its stability and efficiency surpass those of systems that depend on a single source [4-7]. Hybrid energy systems can also offer an advantage of reduced operating and maintenance costs by supplying energy from a backup source if one of the sources is intermittent [8].

The majority of studies on hybrid electricity generation systems analyze multi-source electricity generation systems that are entirely composed of renewable energy sources, as evidenced by the literature review. The source configuration that is employed most frequently is wind/solar PV/battery storage. Diesel generators can also be employed to supply power units in renewable-based hybrid energy systems. Additionally, hybrid systems that utilize fuel cells, electrolyzers, or supercapacitors have been the subject of numerous studies. The hybrid energy systems can be configured as grid-connected, off-grid, or as a micro-grid, with the potential to be conditionally independent of the grid or connected to the grid. It has been noted that the primary focus of the studies is the modeling of the hybrid system and energy analysis, as well as the development of an energy system control and management strategy with optimal system sizing. In order to ensure that the electricity demand of rural areas, particularly those that are remote from the central region, is consistently met, numerous studies have implemented system design and analysis that incorporate a variety of renewable energy sources and battery storage components [5-6,8-9]. For instance, in order to satisfy the electricity requirements of a factory situated in Konya district, Tabak (2021) employed the Hybrid Optimization of Multiple Energy Resources (HOMER) software to design and analyze a hybrid energy system that comprises solar PV panels, a battery storage unit, and a diesel generator for backup power. It is found that the designed hybrid system is capable of adequately meeting the electricity demand of the factory [10]. Shahzad et al. (2017) utilized the HOMER tool to design a hybrid system that combines solar PV and biomass to satisfy the electricity needs of a farm located in a rural region of Pakistan. They conducted sensitivity analyses for a variety of biomass potentials, solar radiation, and loads [11]. Similarly, in order to meet the electricity requirements of Central Classroom-2 at Kırklareli University Kayalı Campus, Dursun (2016) implemented a techno-economic optimization study utilizing HOMER software to identify the most appropriate hybrid system comprised of wind, solar, and biomass resources [12]. In the study of Gubański et al. [28], the functioning of a hybrid micro-grid system including a wind turbine, photovoltaic solar panel, and electricity storage unit was created and modeled at the university research center. By examining the load characteristics and power curves of certain equipment, as well as in response to weather conditions, the wind-solar hybrid system showed erratic electricity output. The study also looked into the results of several wind turbine and solar panel technologies. An off-grid hybrid renewable energy system was proposed by Roy et al. [29] that combines battery storage, an electrolyzer and renewable energy sources based on wind, solar PV, and biogas. The purpose of this system is to meet the village community's electrical needs. To improve the equipment sizing, a multi-criteria decision-making methodology utilizing the TOPSIS method was adopted. The system's objective function was to reduce the levelized cost of electricity (LCOE). The system's ability to produce power, net present value of costs, LCOE, hydrogen cost, and carbon emissions are examples of economic and environmental factors. The TOPSIS technique calculations were carried out using MATLAB software. The components of the hybrid energy system that maximize system performance in different configurations were identified based on their power and capacity.

Türkiye's renewable energy strategies and policies prioritize the most effective use of renewable energy potential to enhance the security of electricity supply, address the ongoing climate crisis, and reduce detrimental carbon emissions [13]. In this way, hybrid energy technologies make use of the advantages of renewable energy resources when used in conjunction and as an auxiliary source. The multi-source electricity production method is the regulatory definition of this relatively new energy system in the Turkish electricity market. In February 2019, the Electricity Market Law (No: 6446) was amended to introduce multi-source electricity production technology into Turkish electricity market regulation for the first time. The Energy Market Regulatory Authority (EMRA) prepared the secondary legislation related to the prelicense or license application procedures and principles and this regulation entered into force in July 2020. Subsequently, the EMRA began receiving applications for multi-source electricity production facilities. A new prelicense application can be submitted to the EMRA for the construction of a multi-source electricity production facility, or the auxiliary source units can be established within the existing power plants by an amendment to the electricity production licenses, as per the legislation [14].

The allocation of capacities to secondary source units in multi-source electricity production systems is currently restricted by the primary source type and installed capacity, as per the current regulation. Additionally, there is a distinct capacity allocation methodology for multi-source electricity production systems, in which the primary source types are different from wind or solar, and the auxiliary source type relies on wind or solar. Consequently, the objective of this paper is to evaluate the impact of the current regulation by examining the allowable capacities and comparing them to the real-world data as of June 2024, with a particular emphasis on the capacity constraints and capacity allocation mechanism for hybrid electricity generation systems. This is accomplished by comparing the allowable capacities to the real-world data as of June 2024. The evaluation and comparison of the utmost allocable capacities and realizations facilitate the assessment of the effectiveness of the multi-source electricity generation regulation and the progress of these systems in Türkiye. Furthermore, our objective is to identify potential modifications and provide suggestions for the continued improvement of these more stable and environmentally friendly energy systems. This study's fundamental contributions include the identification of the current regulation for the hybrid electricity production systems in Türkiye, the comparison of the maximum allowable capacities for the secondary source units to the recently collected actual-life data, including primary and secondary resource configurations, and the formulation of policy recommendations for the continued development of the hybrid energy systems in Türkiye.

The paper is organized in the following manner. Part 2 provides a comprehensive explanation of the multi-source electricity production regulation, including the licensing procedures, the most significant subjects for the capacity allocation mechanism for these systems, and incentive mechanisms. The data that was collected for the analyses is also presented in this section. The utmost allocable capacities for the auxiliary source units and capacity allocations for the auxiliary sources approved by the EMRA as of June 2024 with respect to twelve distinct connection regions determined by Turkish Electricity Transmission Company (TEIAS) are demonstrated in Part 3. The paper is concluded in Part 4 by summarizing the most significant aspects of the study and expressing a variety of policy recommendations for the effective development of hybrid electricity production systems in Türkiye.

2. MATERIAL and METHOD

In Türkiye, the electricity market legislation requires capacity allocation auctions to be held in order to give prelicenses and licenses for the building of wind or solar-based licensed power plants [15]. This might be attributed to the intense competition in the wind and solar power investment industry and the abundant resource potential of these renewable energy sources in Türkiye. The applications for multi-source electricity production systems are not subject to an auctioning procedure. However, the legislation establishes capacity limitations based on the primary or secondary source type and installed capacity. The following section defines the specifics of the regulation that governs multi-source energy systems.

2.1. The Turkish Electricity Market Regulation on Multi-Source Electricity Production Method

Hybrid electricity production systems may be assessed in three distinct categories in the literature. The initial model is the combined electricity production model, which involves the integration of electricity generation units that utilize diverse energy resources. These units are utilized in the same power plant zone, using the same grid infrastructure. Some examples of this system include hydro/solar PV, hydro/wind, and wind/solar PV. The co-firing electricity production model is the second form of hybrid energy systems. In this model, electricity is produced by processing two distinct sources in the same production facility and in the same process, such as the combustion of coal and biomass in the same boiler. These systems may employ coal/biomass or gas/biogas resources. The final type of hybrid energy systems is the supporting-source electricity production model, which improves the system's effectiveness by utilizing a supporting secondary source, such as solar power in a geothermal or coal-based power plant [16,17].

By amending the Electricity Market Law (Law No: 6446) and the Law on Utilization of Renewable Energy Resources for the Generation of Electricity (Law No: 5346) on 28 February 2019 (amending law no: 7164), the multi-source electricity production model has been incorporated in the Turkish electricity market regulation to improve the energy efficiency of existing power plants and boost the utilization of renewable energy sources [18]. The changes to the laws ensure that principles and procedures governing prelicense applications, amendment of licenses, and implementation of the Renewable Energy Resources Support Mechanism (YEKDEM) for the multi-source electricity production facilities will be regulated by the secondary legislation to be prepared by the EMRA.

The corresponding amendments to the By-Law for Electricity Market Licensing and By-Law for Certification and Support of Renewable Energy Resources were prepared by the EMRA and enacted on 1 July 2020 [19,20]. As per the regulations in force, auxiliary source units must be constructed within the power plant premises of the primary source unit. Hence, to precisely determine the geographic coordinates of power plant sites and the units to be included within the power plant zones for each energy resource and technology type, EMRA has prepared an additional secondary legislation. This legislation, known as "The Principles and Procedures for Determining Power Plant Sites of Prelicensed and Licensed Power Plants" was published in the Official Gazette on 1 July 2020 [21]. EMRA has started to receive applications for establishment of multi-source electricity production facilities since then.

Figure 1 provides a summary and demonstration of the chronological development of primary and secondary legislation pertaining to multi-source electricity generation systems.

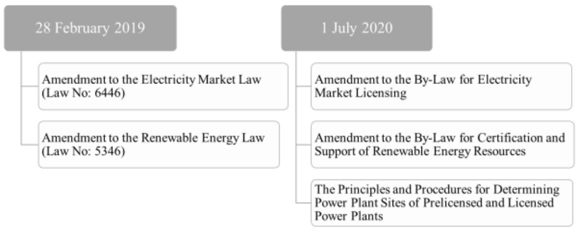

Figure 1. The regulatory development of the multi-source electricity production system in the Turkish electricity market.

The By-Law for Electricity Market Licensing contains the technical definitions of the multi-source electricity production systems that can be established, the categories of power plants, the licensing rules, and the rights and obligations of prelicense or license owners [14]. In addition, the By-Law for Certification and Support of Renewable Energy Resources includes regulations regarding the methodology for YEKDEM implementation in multi-source electricity production systems [23]. The hybrid energy systems in the Turkish electricity market are primarily classified according to the hybrid systems specified in the literature. Although hybrid energy systems may incorporate components such as a storage unit, diesel generator, fuel cell, electrolyzer, or supercapacitor, they are currently being developed in Türkiye as the installation of auxiliary source units utilizing a secondary electricity generation source in addition to the primary source. By utilizing auxiliary source units, intermittent and variable feature of single-source power plants is mitigated and electricity can be produced more reliably with increasing flexibility in the energy system. Moreover, the amount of renewable electricity generation increases in the hybrid systems with the construction of renewable-based auxiliary units. Consequently, the implementation of the regulation regarding multi-source electricity production systems in Turkish electricity markets has enabled investors to regulate electricity production in a more manageable fashion than single-source power plants.

Figure 2 illustrates the classification of multi-source electricity production methodologies as outlined in the legislation. These methods include the combined electricity production model, the combined renewable electricity production model, the supporting-source electricity production model, and the co-firing electricity production model. Investors interested in the establishment of hybrid electricity production systems have the option of submitting a direct prelicense application to the EMRA or an application for the amendment of their current licenses with an aim of adding auxiliary source units to their power plants. Prelicense is a temporary authorization granted by the EMRA to legal entities that intend to engage in licensed electricity production activities in order to acquire the requisite certifications, permits, and other forms of authorization to commence production facility investments [15]. The applications to construct auxiliary source units are made and evaluated by considering the primary and secondary source types, as well as the allowable connection capacities. The capacity limits defined in the legislation should also be satisfied for the auxiliary source investments.

In addition, the auxiliary source units based on solar energy can be built as floating-solar units by taking necessary permissions for the usage rights of the water resources from the General Directorate of State Hydraulic Works. The installed electrical capacity (MWe) of the power plant cannot be exceeded, therefore the capacity of auxiliary source units, which is counted as back up units, are written on prelicenses or licenses in terms of mechanical capacity (MWm). When forming the existing power plant based on single resource to a multi-source electricity production facility, the power plant site, grid connection configuration and voltage level cannot be modified. In addition, it is required that TEIAS and/or the related distribution company must give positive technical opinion regarding the system connection and capacity allocation for the hybrid energy project. In the same vein, the technical evaluation carried out by the Directorate General of Energy Affairs must be appropriate for the applications if the auxiliary source units are solar or wind-based. On the other hand, the regulations concerning the implementation of YEKDEM for the hybrid systems are included in the Article-4 of the By-Law for Certification and Support of Renewable Energy Resources for combined renewable and supporting-source type electricity production models. The legislation stipulates that the net quantity of energy produced in the combined renewable electricity production system and supplied to the grid within the scope of YEKDEM will be subject to the lowest support price of the renewable energy resources used in the production facility.

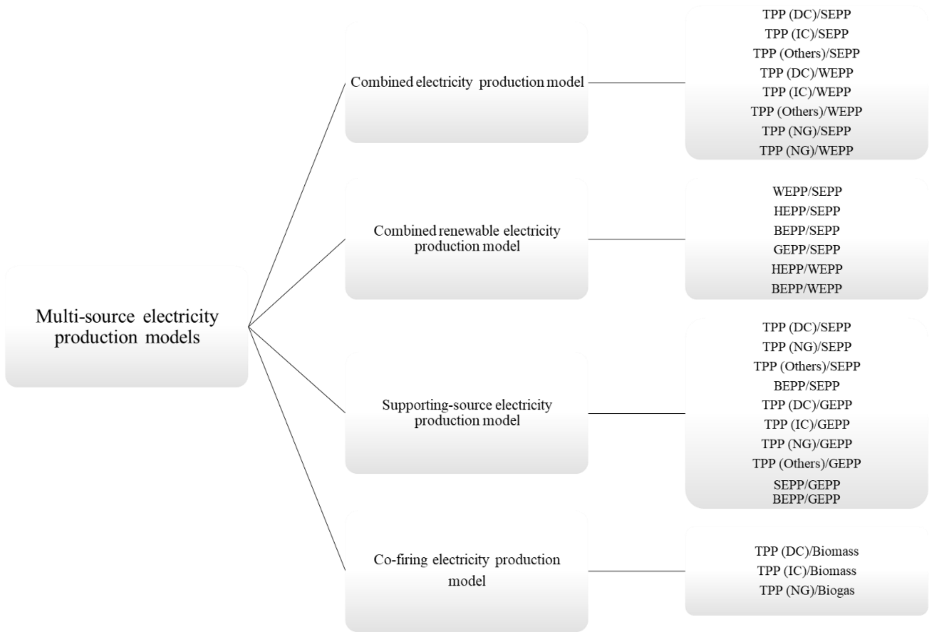

Figure 2. The multi-source electricity production models described in the legislation and sample power plant configurations.

This price will be in effect for the remainder of the production facility's YEKDEM duration. Similarly, on the condition that all of the energy resources utilized in the facility are renewable, the net amount of energy produced in the supporting-source electricity generation facility and supplied to the grid will be considered within the scope of YEKDEM at the support price of the primary source. This price will be applied for the remainder of the YEKDEM duration of primary source units [23]. Thus, hybrid systems utilizing two or more renewable energy resources may benefit from guaranteed prices within YEKDEM mechanism with the increased net electricity production.

In addition to the regulations outlined in the By-Laws for the licensing procedures and YEKDEM implementation for multi-source electricity production systems, the Principles and Procedures for Determining Power Plant

Sites of Prelicensed and Licensed Power Plants, Article-24, provide a description of the capacity limits that apply to auxiliary source units. The methodology described in the legislation by the EMRA is presented in Figure 3, which is a representation of the utmost mechanical capacities (MWm) that auxiliary source units can have in relation to the electrical capacity of the primary source unit. Besides, the maximum capacity of auxiliary source units is restricted to 100 MWm in all cases, unless the primary source unit is of wind-based. These capacity constraints set a framework for the maximum capacities that can be allocated to the auxiliary sources in multi-source electricity production systems. According to this regulation, if the primary source unit's capacity is lower than 50 MWe, the auxiliary source units can be built up to the primary source's electrical capacity, and if the primary source unit's capacity is higher than 50 MWe, the maximum capacity of auxiliary source units is restricted with the formulation given in Figure 3. Similarly, the maximum capacity of the auxiliary source units is limited to 100 MWm except for the wind power plants. This is due to the fact that wind and solar resources can more easily hybridized by taking into account their intermittent and complementary characteristics, also the costs and ease of investment. Thus, in order to facilitate the hybrid use of wind and solar units, the wind power plants are excluded from 100 MW capacity limit.

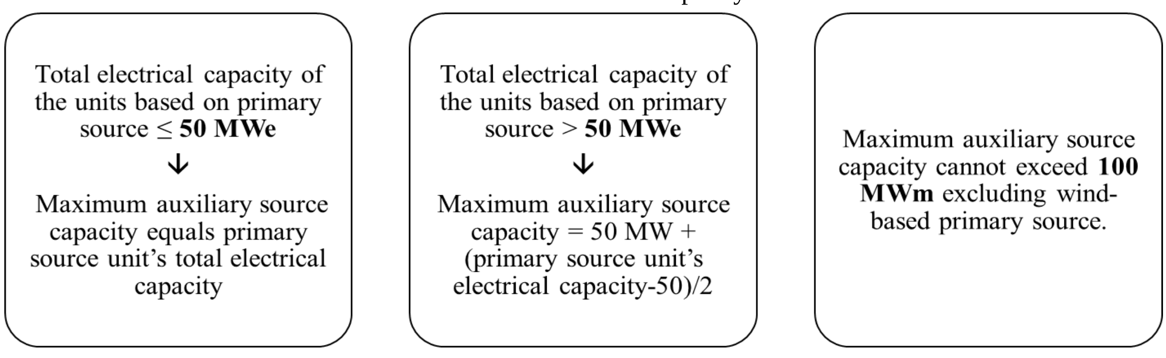

Figure 3. The maximum capacity limits for auxiliary source units of multi-source electricity production facilities described in the secondary legislation [21].

After the EMRA began receiving license applications for the construction of auxiliary source units, the provisional Article-29 of the Electricity Market Law (amending law no: 7257) was published in the Official Gazette on 25 November 2020 [15]. This provision granted legal entities the authority to amend their prelicenses or licenses by reducing the installed capacity of the projects or to terminate the prelicenses or licenses. In this context, 1026 MW of wind-based connection capacity was released. In addition, the release of additional wind or solar power connection capacities over time is a result of the numerous capacity reductions of Renewable Energy Zone projects. The Board of EMRA adopted a new methodology for the allocation of this total capacity for multi-source electricity production systems that have a primary source that is not wind or solar-based, but an auxiliary source that is wind or solar-based, in response to the technical opinions of TEIAS. Specifically, these hybrid systems are subject to these regional capacity limits if the primary sources are hydroelectric, geothermal, biomass, or thermal, and the auxiliary sources are wind or solar. The primary sources defined previously provide more regular electricity production than wind or solar resources, therefore the auxiliary source units to be constructed in such power plants are more competitive and capacities to be allocated for these power plants are thus limited. EMRA also determined that the capacities will be specified on a regional basis. Therefore, TEIAS disclosed twelve distinct connection regions as illustrated in Figure 4 and connection capacities for the auxiliary sources of the aforementioned multi-source energy systems.

Figure 4. The connection regions that TEIAS designated for the capacity allocations to the auxiliary source units of multi-source electricity production systems.

The methodologies for allocating the allowable capacities for the aforementioned multi-source electricity production systems were the subject of decisions issued by the Board of EMRA on 26 August 2021 (Decision No: 10375), 3 March 2022 (Decision No: 10822), and 1 September 2022 (Decision No: 11160). In this manner, the allocable capacities for the auxiliary source units of multi-source electricity production systems for which the primary sources are not wind or solar and the auxiliary sources are wind or solar were calculated as 2104.02 MW in total and represented in Table 1. These capacities were calculated by means of the notices of TEIAS in various dates in their web site [24].

2.2. Analysis of the Allowable Capacities and Data Collection

As previously described, the capacity allocation process for the auxiliary sources of the multi-source electricity production systems in Türkiye is contingent upon the installed capacity of the primary source units and the primary and secondary source types. A summary of the capacity allocation methodology is presented in Figure 5, which is organized by the types of primary and secondary sources. Figure 5 shows that the capacity limits for the auxiliary sources mainly depend on whether the primary or secondary source type is wind or solar.

Table 1. The regional allocable capacities declared by TEIAS for the hybrid electricity production systems whose primary sources are not based on wind or solar and auxiliary sources are wind or solar-based.

Connection Region No.	Regional Allocable Capacity (MWm)
1	88
2	307.14
3	184.88
4	217.35
5	388.1
6	195.6
7	132.22
8	121.51
9	137
10	174.02
11	70
12	88.2
Total	2104.02

In this study, we examined multi-source electricity production systems by taking into account that the primary sources are based on solar (SEPP), wind (WEPP), geothermal (GEPP), hydroelectric (HEPP), biomass (BEPP), natural gas (TPP (NG)), domestic coal (TPP (DC)), import coal (TPP (IC)), and other thermal (TPP (Others)), which contains nuclear and petroleum products. Furthermore, it was presumed that secondary sources would exclusively be renewables, including SEPP, WEPP, GEPP, HEPP, and BEPP. We only considered licensed power plants and did not consider the prelicenses granted for multi-source energy systems, as the prelicense does not guarantee the issuance of a license and the realization of the project.

The allowable connection capacities were determined and calculated in accordance with the decisions of the Board of EMRA dated 26 August 2021 (Decision No: 10375), 3 March 2022 (Decision No: 10822), and 1 September 2022 (Decision No: 11160), as well as the notices of TEIAS that corresponded to these Board decisions. EMRA database was used to collect numerical data on the licensed power plant projects, including data for the primary sources and real-life data for license amendments. This data includes information such as the capacity, type of resources, and location of the projects. The data utilized was collected on 13 June 2024 [25]. So as to determine the maximum capacities that can be allocated to the auxiliary sources of hybrid electricity production systems in accordance with the regulation in Article-24 of the Principles and Procedures for Determining Power Plant Sites of Prelicensed and Licensed Power Plants (as illustrated in Figure 3), we used the data for licensed projects and calculated the allowable auxiliary source capacity for each power plant using a Microsoft Excel formula. Subsequently, we classified these auxiliary source capacities according to twelve connection regions and primary source groups.

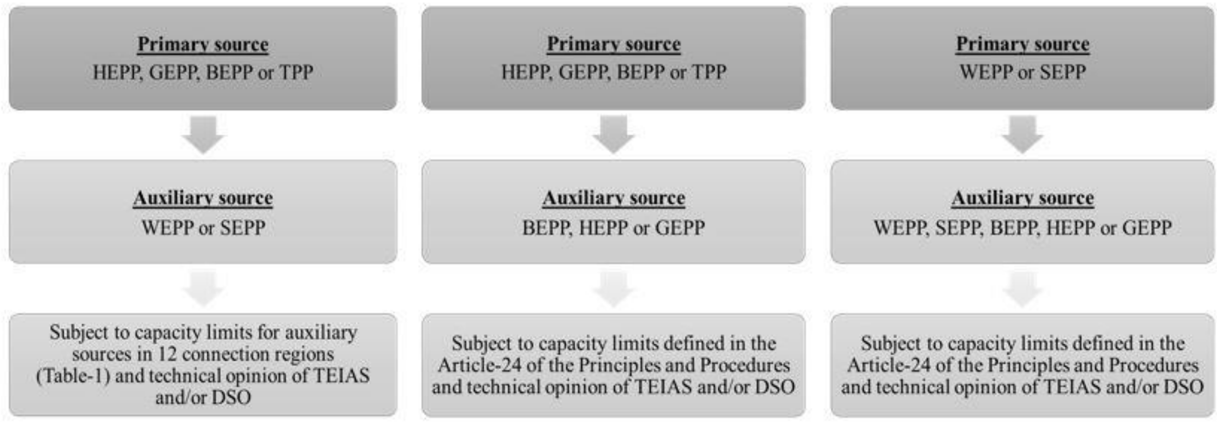

Figure 5. The capacity allocation methodology for multi-source electricity production systems with respect to primary and auxiliary source types.

3. RESULTS AND DISCUSSION

3.1. Results of Capacity Allocations for Auxiliary Sources

The greatest allocable capacities were determined and demonstrated in Table 2 in accordance with the regulation outlined in Part 2 regarding the capacity constraints for the secondary sources. The total installed capacity of auxiliary sources that can be constructed is 44747.48 MWm. The null values in Table 2 indicate that there are no licensed power plant projects for the related primary source type in the corresponding region. Consequently, no auxiliary source unit can be installed in that region based on the related primary source.

The real-world data regarding the capacities allocated to the auxiliary sources as of June 2024 were calculated using the completed licensed amendments and shown in Table 3 with respect to primary and auxiliary source types and connection regions. The share of the total capacity allocated in terms of secondary source types is also illustrated in Table 4.

Table 2. The maximum allocable capacities for the auxiliary sources on connection region basis with respect to various kinds of primary sources (Own depiction based on data for the licensed projects [25]).

Primary source type	**SEPP**	**WEPP**	**GEPP**	**HEPP**	**BEPP**	**TPP (NG)**	**TPP (DC)**	**TPP (IC)**	**TPP (OTHERS)**	**TOTAL**
Connection region no.										
1	-	1700.20	-	-	456.57	1252.09	-	-	10.81	3419.66
2	14.00	6193.74	1419.46	674.26	427.36	993.64	890.66	692.50	259.21	11564.83

Table 2. (cont.) The maximum allocable capacities for the auxiliary sources on connection region basis with respect to various kinds of primary sources (Own depiction based on data for the licensed projects [25]).

3	-	623.00	13.00	512.32	206.98	1005.08	450.50	117.53	175.19	3103.59
4	99.00	216.65	280.21	745.21	162.52	269.25	5.50	5.00	14.82	1798.16
5	440.12	1046.10	2.76	1052.94	435.18	274.38	-	77.33	167.20	3496.00
6	-	312.30	-	798.85	240.42	488.98	128.00	8.70	102.68	2079.93
7	-	125.00	-	292.71	95.82	125.62	-	287.25	7.32	933.71
8	9.00	562.95	-	1937.80	103.40	229.55	100.00	7.76	35.35	2985.81
9	67.00	1241.69	-	2944.36	249.47	417.86	300.00	377.98	148.66	5747.01
10	186.94	167.60	-	2080.02	159.57	172.08	-	-	5.80	2772.01
11	4.90	194.62	-	5150.03	88.30	9.60	-	-	20.90	5468.35
12	97.85	137.95	-	983.43	26.72	7.68	100.00	-	24.80	1378.43
TOTAL	918.81	12521.79	1715.42	17171.92	2652.30	5245.80	1974.66	1574.05	972.74	44747.48

Table 3. The capacities allocated to the auxiliary sources on connection region basis with respect to various kinds of primary sources(Own depiction based on license amendments for multi-source electricity production systems [25]).

	Primary source type	**WEPP**	**GEPP**	**HEPP**	**BEPP**	**TPP (NG)**	**TPP (DC)**	**TPP (IC)**		**TPP (OTHERS)**	**Total realized capacity**
	Auxiliary source type	**SEPP**	**SEPP**	**SEPP**	**SEPP**	**SEPP**	**SEPP**	**SEPP**	**BEPP**	**SEPP**	
Connection region no.	1	20.19	-	-	10.51	15.42	-	-	-	-	46.12
	2	700.33	22.84	1.88	10.00	18.75	100.94	11.55	6.17	-	872.45
	3	53.43	-	7.30	19.26	5.66	38.01	-	-	-	123.65
	4	88.52	71.52	8.15	13.31	7.88	-	-	-	-	189.37
	5	352.77	-	25.93	113.86	10.73	-	5.55	-	-	508.84
	6	96.64	-	22.09	26.89	-	-	-	-	21.88	167.50
	7	35.00	-	6.76	-	11.48	-	-	-	-	53.24
	8	146.73	-	35.32	-	-	-	-	-	-	182.05
	9	269.17	-	13.54	1.46	-	16.34	70.40	-	0.07	370.97
	10	19.84	-	150.07	30.40	-	-	-	-	-	200.31
	11	30.00	-	16.54	5.37	-	-	-	-	-	51.91
	12	50.00	-	41.99	-	-	-	-	-	5.00	96.99
	TOTAL	1862.63	94.36	329.58	231.06	69.91	155.28	87.49	6.17	26.94	2863.41
		1862.63	94.36	329.58	231.06	69.91	155.28	93.66		26.94	
		2863.41									

Table 4. The share of capacity allocations with respect to auxiliary source types.

Auxiliary source type	**Installed capacity (MWm)**	**Share (%)**
SEPP	2857.24	99.8%
BEPP	6.17	0.2%
WEPP	0.00	0.0%
GEPP	0.00	0.0%
HEPP	0.00	0.0%
TOTAL	2863.41	100.0%

In Figure 6, the capacities of auxiliary sources that have been allocated and the license amendment procedure has been finalized are compared to the total allowable capacities in twelve connection regions. In this figure, the realization rates associated with each connection region were also highlighted. The realization rate represents the ratio of the quantity of capacity that has been allocated and issued on the license as of June 2024 to the maximum capacity that can be allocated for each connection region. In addition, Figure 7 illustrates the total capacities allocated to the auxiliary sources in twelve connection regions as of June 2024, with respect to each primary source and auxiliary source configuration. Because there is a distinct capacity allocation approach for multi-source electricity production systems in which the primary sources are not solar or wind-based but the auxiliary sources are solar or wind-based, the results for these hybrid energy systems were examined independently. As a result, we calculated and provided the capacities allocated to the auxiliary sources of these hybrid systems in Table 5.

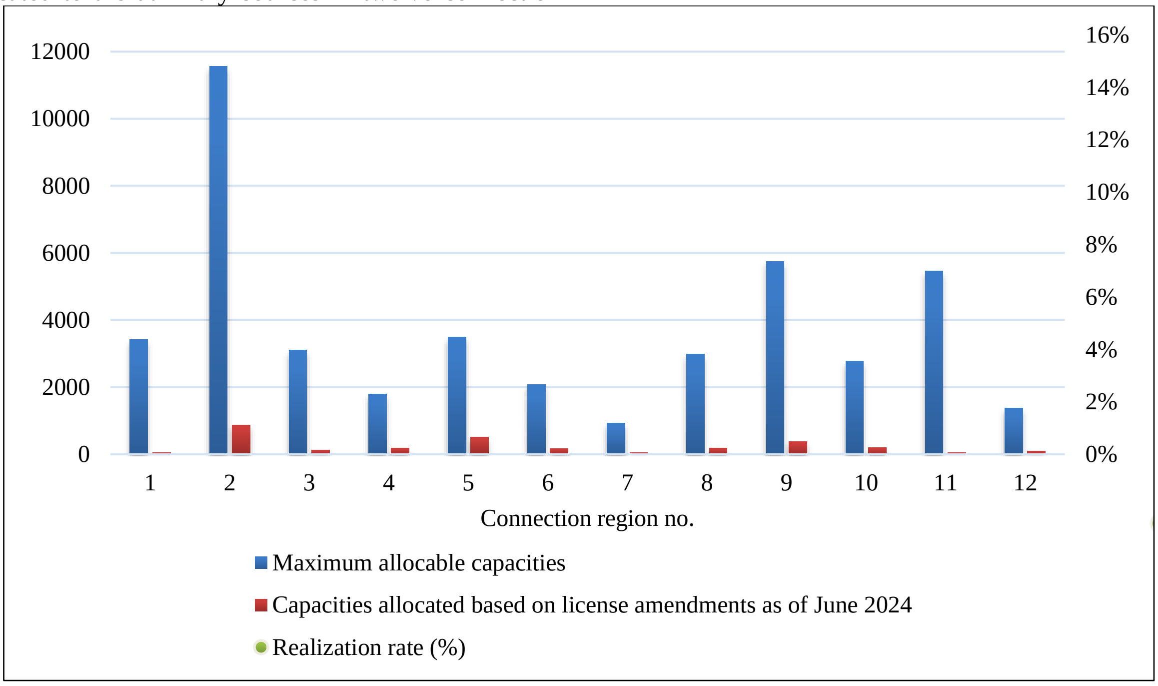

Figure 6. Comparison of the maximum allowable capacities and capacities allocated to the auxiliary sources as of June 2024.

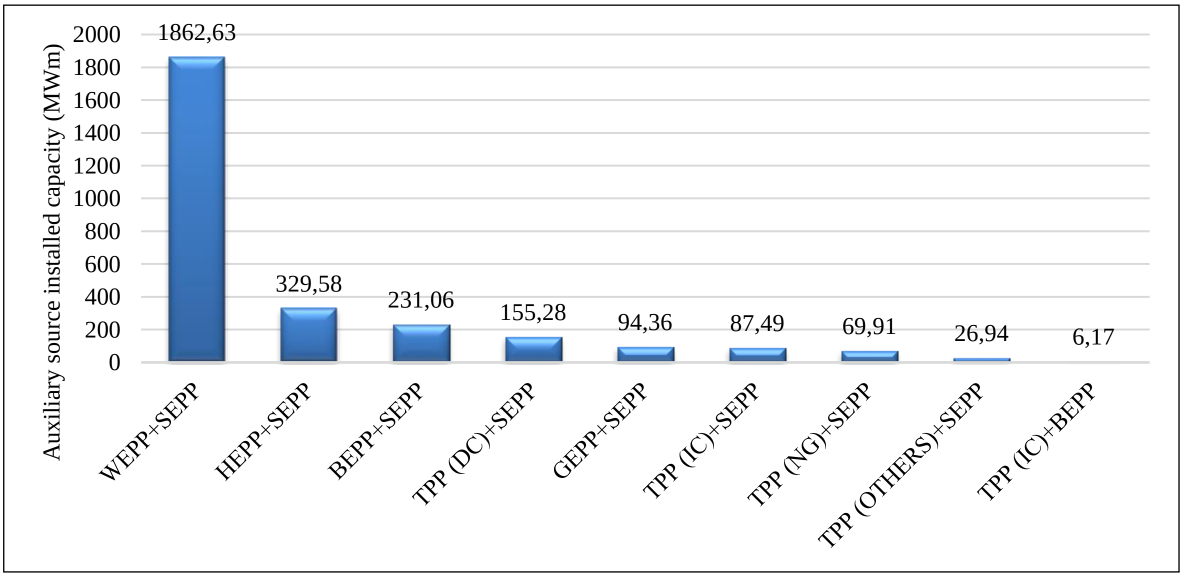

Figure 7. The capacities that have been allocated for each primary source plus auxiliary source configuration.

Table 5. The capacities allocated to the solar or wind-based auxiliary sources on connection region basis for which the primary sources are not based on solar or wind.
(Own depiction based on license amendments for multi-source electricity production systems [25]).

	Primary source type	**GEPP**	**HEPP**	**BEPP**	**TPP (NG)**	**TPP (DC)**	**TPP (IC)**	**TPP (OTHERS)**	**Total realized capacity**
	Auxiliary source type	**SEPP**	**SEPP**	**SEPP**	**SEPP**	**SEPP**	**SEPP**	**SEPP**	
Connection region no.	1	-	-	10.51	15.42	-	-	-	25.93
	2	22.84	1.88	10.00	18.75	100.94	11.55	-	165.96
	3	-	7.30	19.26	5.66	38.01	-	-	70.22
	4	71.52	8.15	13.31	7.88	-	-	-	100.86
	5	-	25.93	113.86	10.73	-	5.55	-	156.07
	6	-	22.09	26.89	-	-	-	21.88	70.86
	7	-	6.76	-	11.48	-	-	-	18.24
	8	-	35.32	-	-	-	-	-	35.32
	9	-	13.54	1.46	-	16.34	70.40	0.07	101.80
	10	-	150.07	30.40	-	-	-	-	180.47
	11	-	16.54	5.37	-	-	-	-	21.91
	12	-	41.99	-	-	-	-	5.00	46.99
	TOTAL	94.36	329.58	231.06	69.91	155.28	87.49	26.94	994.62
		994.62							

3.2. Discussions

In the preceding section, the maximum allocable capacities on a twelve-connection region basis were determined by examining the relevant legislation, and the realizations based on the capacity allocations to the auxiliary sources of multi-source electricity production systems as of June 2024 were calculated and demonstrated. The results indicate that the total capacity allocated for the auxiliary sources based on the real-world data is 2.86 GW which is equivalent to 6.4% of the total capacity, despite the fact that the total allowable capacity is 44.7 GW. Nevertheless, the establishment of hybrid power plants is constrained by a variety of factors, including the availability of project area for the construction of auxiliary source units inside the present single-source power plants, the suitability of the infrastructure, financial issues, and the availability of resource potential. Thus, although the theoretically determined allowable capacity is 44.7 GW, in reality, the quantity of available capacities for auxiliary sources is anticipated to be lower as a result of these challenges.

The HEPP type primary source has the highest value for the available auxiliary source capacity, followed by WEPP, TPP (NG), and BEPP, in terms of maximal capacities to be allocated. However, the utilization of the available capacities is restricted by the capacities announced by TEIAS, as HEPP, GEPP, BEPP, and TPP type primary sources are subject to regional capacity limits when the auxiliary sources are solar or wind, as illustrated in Table 1. The available capacities for these primary sources may be readily utilized if the auxiliary source is different from solar or wind. For instance, the construction of an auxiliary source unit of the BEPP type in GEPP or TPP would be feasible as long as the investment is financially viable and there is available resource potential. In practice, solar PV is the primary auxiliary source, accounting for 99.8% of the total capacity allocations, as it offers a relatively homogeneous and abundant resource potential in all regions of Türkiye, as well as a relatively reduced investment cost and ease of construction. Solar PV is also a great option for obtaining backup power during the day. In fact, there is only one project that employs BEPP as an auxiliary source, in addition to solar PV.

The real-world data shows that the capacity allocated to construct auxiliary source units in SEPP is zero, despite the fact that the SEPP primary source type power plants have a 918.81 MWm auxiliary source capacity, as evidenced by Table 2 and Table 3. In practice, solar and wind resources can be combined and used commonly in hybrid form due to their complementary electricity production characteristics. This is because both are intermittent resources, and electricity is most efficiently generated during distinct hours of the day. Consequently, the construction of wind-based auxiliary source units in solar power plants may be feasible in a variety of connection regions (2,4,5,8-12) as long as the resource potential and infrastructure of the power plant zone are suitable. Additionally, the WEPP+SEPP primary and auxiliary source configuration has the highest capacity allocation in the actual case followed by HEPP+SEPP, BEPP+SEPP, TPP (DC)+SEPP and GEPP+SEPP. This is due to the fact that WEPP is subject to capacity limits that are exclusively defined in Article-24 of the Principles and Procedures for Determining Power Plant Sites of Prelicensed and Licensed Power Plants, and it is exempt from the maximum auxiliary source capacity of 100 MWm that is applicable to other primary source types. Further, it is feasible to allocate additional auxiliary source capacities for WEPP type primary sources in the first, second, fifth, and ninth connection regions, as the installed capacity of WEPPs and the potential of wind and solar power resources in these regions are exceedingly high.

The auxiliary source capacities granted for renewable-based primary sources outnumber the capacities allocated for TPPs. Thus, we can conclude that hybrid energy systems are mostly implemented as combined renewable electricity production model in Türkiye.

Upon comparison of the allowable capacities and realized values across twelve connection regions, the fifth, fourth, sixth, and second connection regions exhibit the highest realization rates. The main reason for this outcome is the substantial biomass and solar energy potential in the fifth region, as well as the widespread demand for solar PV auxiliary source installations in GEPPs in the fourth region. We can also assert that there is a significant quantity of available capacity for the installation of auxiliary sources in thermal power plants in all connection regions. The building of auxiliary source units that are based on renewable energy sources in TPPs has the potential to reduce detrimental carbon emissions that are caused by the use of fossil fuels in these facilities, thereby enabling more sustainable electricity generation. However, the realization of these investments necessitates the availability of additional connection capacities.

Lastly, the comparison of the realized data for multi-source electricity production systems in which the primary sources are not based on wind or solar, and the auxiliary sources are wind or solar-based, with the regional connection capacities depicted in Table 1 reveals that the total capacity allocated for these types of hybrid system configurations whose licenses have been amended is 994.62 MWm as of June 2024, while the total allowable capacity is 2104.02 MWm. Consequently, 34.7% of the total available capacity in twelve connection regions has been allocated. TEIAS may have allocated the remaining capacities for the license amendment applications; however, they have not yet been approved by the EMRA. The lowest realization rates have been observed in the seventh, eighth, first, and eleventh connection regions, which are attributed to the relatively low solar energy potential in these regions. Thus, it can be said that in addition to technical and financial concerns, the availability of resource potential is also a critical factor in the establishment of auxiliary source units.

4. CONCLUSION

Hybrid electricity production systems are innovative energy technologies that enable the integration of multiple resources within a single power plant by utilizing the same utility networks and power plant site. They improve grid stability by reducing system costs and enabling more sustainable and flexible electricity production. In practice, hybrid energy systems are frequently employed to electrify remote locations, such as rural areas and islands, in a stand-alone mode. This is achieved by incorporating battery storage units and diesel generators to satisfy the required electricity demand.

Through the completion of secondary legislation, the Turkish electricity market has implemented a multi-source electricity production model since July 1, 2020. The authority responsible for granting and issuing licenses to investors who are interested in constructing auxiliary units within the context of these systems is EMRA. Thus, the objective of this study is to evaluate the regulation of multi-source electricity production systems in Türkiye, with a particular emphasis on the capacity constraints and capacity allocation methodology.

According to the results acquired, 6.4% of the maximum installed capacity of the auxiliary sources has been achieved as of June 2024. This indicates that there is still a significant amount of potential for the construction of hybrid energy systems in Türkiye. In this context, the capacity allocation mechanism for the HEPP, BEPP, GEPP, and TPP type primary sources, as well as the legal permission procedures, must be facilitated, and additional connection capacities must be declared to boost the investments in the hybrid energy systems.

According to TEIAS data, the installed capacity of Türkiye has attained 110.5 GW, with a 57.3% share of renewables in this capacity as of June 2024 [26]. In addition, the National Energy Plan of Türkiye [13] suggests that the total installed capacity of the country will increase to 189.7 GW, solar-based installed capacity to 52.9 GW, wind-based installed capacity to 29.6 GW, the share of renewable-based total installed capacity to 64.7%, and the share of intermittent resources' (solar and wind) installed capacity to 43.5% in 2035. In the same vein, it is anticipated that the electrolyzer capacity will be 5 GW and the battery storage capacity will be 7.5 GW by 2035. Auxiliary sources built into multi-source electricity production systems, which are primarily solar PV in the actual case, generate additional electricity from renewable sources. Consequently, the role of hybrid electricity production systems will be crucial in achieving the renewable energy targets, particularly for solar and wind power. The integration of battery storage units, electrolyzers, and fuel cells into these systems can also be advantageous in terms of improving grid stability and efficiently utilizing excess electricity for green hydrogen production. The multi-source electricity production systems should also be prevalent in distributed electricity production systems (unlicensed electricity production model according to the Turkish electricity market legislation) to facilitate more efficient and adaptable electricity production systems. Thus, it is imperative to establish regulations for these alternative hybrid energy systems in order for Türkiye to combat climate crisis more effectively and to reach 2053 net zero emission targets in a more systematic way.

Additionally, the electricity produced in the combined renewable electricity production systems can benefit from YEKDEM over the lowest price of each resources' support price used in the hybrid power system. In practice, when we examine the final YEKDEM list for 2024 announced by EMRA [27], there are 161 multi-source power plants (the auxiliary source units are in operation for 35 projects) which are in the scope of YEKDEM. All of the auxiliary sources are solar-based and the YEKDEM support price of solar is 13.3 US Dollar cents/kWh which is highest among other renewable energy sources. Consequently, the hybrid energy systems are subject to the support price that corresponds to the primary sources, and the construction of solar-based auxiliary sources does not result in any financial disadvantages in the support of renewable energy production.

Finally, it has been noted that progress has been made in the construction of solar-based auxiliary source units in Türkiye's multi-source electricity production systems. In order to attract investors' interest in the establishment of auxiliary source units other than solar PV, such as WEPP, BEPP, or GEPP, and the construction of supporting-source or co-firing power plants, additional financial incentives can be provided, such as direct investment payments or the implementation of various support schemes. These measures are essential for the purpose of increasing the proportion of renewable energy in Türkiye's electricity system as it proceeds along the clean energy transition path.

SYMBOLS AND ABBREVIATIONS

BEPP	Bioenergy Power Plant
DSO	Distribution System Operator
EMRA	Energy Market Regulatory Authority of Türkiye
GEPP	Geothermal Energy Power Plant
HEPP	Hydroelectric Energy Power Plant
HOMER	Hybrid Optimization of Multiple Energy Resources
HRES	Hybrid Renewable Energy System
LCOE	Levelized Cost of Electricity
MENR	Republic of Türkiye Ministry of Energy and Natural Resources
MWe	Installed Electrical Capacity
MWm	Installed Mechanical Capacity
PV	Photovoltaic
SEPP	Solar Energy Power Plant
TEIAS	Turkish Electricity Transmission Company
TPP (DC)	Thermal Power Plant Utilizing Domestic Coal
TPP (IC)	Thermal Power Plant Utilizing Import Coal
TPP (NG)	Thermal Power Plant Utilizing Natural Gas
TPP (OTHERS)	Thermal Power Plant Utilizing Petroleum Products or Uranium
WEPP	Wind Energy Power Plant
YEKDEM	Renewable Energy Resources Support Mechanism

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DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Mehmet Yalılı: Literature review, analysis of the hybrid electricity production regulation, data collection and compilation, visualization, interpretation of the results, writing and reviewing the article.

Tayfun Menlik: Literature review, analysis of the hybrid electricity production regulation, interpretation of the results, supervision, reviewing the article.

Fatih Emre Boran: Literature review, analysis of the hybrid electricity production regulation, interpretation of the results, supervision, reviewing the article.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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