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Spatiotemporal analysis framework for identifying emerging hot spots and energy potential from livestock manure in Turkey

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ABSTRACT

Biogas technology offers both an environmentally sustainable solution for livestock manure and generates renewable energy. Renewable energy production from livestock manure highly depends on feedstock availability; therefore, the spatial and temporal variability of livestock manure is critical for its sustainable management via biogas plants. In this regard, this study aims to develop a replicable geographic information system based spatiotemporal method to determine emerging hot spots and power capacities for new biogas plants and capacity expansion for the existing plants. The method was conducted to analyze energy production from livestock manure at district level in Turkey between 2013 and 2019. Spatial dimension consists of 970 districts, which makes this study as the spatially most detailed investigation of energy potential from livestock manure in Turkey, while the temporal dimension consists of 13 time steps. 66 districts were determined as emerging hot spots in which 43 have no biogas plants. These hot spots were specified as districts with high priority for the installation of new biogas plants with power capacities ranging between 6.30 MWe and 22.54 MWe. The total theoretical power capacity was calculated as 640 MWe. Capacity expansions were calculated between 0.52 and 13.87 MWe for the existing 63 biogas plants. The unit cost of electricity generation from livestock manure via biogas plants was calculated greater than the feed-in tariff paid by the government. The method aids in decision-making process of environmentally and economically sustainable livestock manure management planning and biogas investors to direct their investments into profitable locations.

1. Introduction

Unregulated disposal of livestock manure and direct use as fertilizer in farmlands are the two major problems in livestock manure management in Turkey. A new regulation was legislated to control livestock manure management [1]. To be valid from the second half of 2021, this new regulation restricts direct application of livestock manure onto soil. In addition, livestock farms have been made responsible for the proper storage of livestock manure and the development of manure management plans. This regulation also encourages the use of livestock manure for biogas production as a management strategy.

Biogas is produced by the breakdown of organic materials such as manure, agricultural waste, sewage sludge, and food waste in the absence of oxygen. It mainly consists of methane and carbon dioxide that can be converted into heat and electric energy. Biogas is also known as a renewable energy resource. It is widely used in Europe since it has a mature technology. There were 17,783 biogas plants in operation in Europe by the end of 2017 and the majority of them utilize agricultural waste, including livestock manure, as feedstock. Germany alone has 10,971 biogas plants using manure and other biowastes for biogas production [2]. There are only 72 biogas plants (excluding the plants utilizing landfill gas) in Turkey, 63 use livestock manure as feedstock [3]. Considering the number of livestock (evaluated under the study area section) and the need for a livestock manure management strategy, the number and capacity of existing biogas plants are insufficient in Turkey. Biogas energy is also considered as a renewable energy source. Therefore, the purchase of electric energy generated from biogas is guaranteed for the first ten years by a higher feed-in tariff by the government. Installation of new biogas plants or capacity expansion may still require special attention to spatiotemporal variability of feedstock availability for an economically sustainable investment [4]. Knowing where the resources are located and their spatiotemporal trends are important aspects of planning biogas investments.

Biogas potential depends on feedstock availability, which is

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geographically dispersed. Therefore, most of the previous studies involve spatial analysis. Studies considering spatial and temporal aspects together are rare in the literature. Yalcinkaya, for example, investigated the siting, sizing and economic feasibility of management of livestock manure and organic fraction of municipal solid waste (OFMSW) through biogas plants in Izmir, Turkey [5]. In this study, a stepwise methodology was performed. First, a land suitability analysis was conducted to determine the potential biogas plant sites. Then, a location-allocation analysis was conducted to determine the relationship between the number of biogas plants, and plant location, capacity and transportation distances. Finally, an economic assessment was performed to determine the optimum solution out of the potentials. The most recent annual average feedstock availability, and collection of all livestock manure and OFMSW were considered in this study. Sharma et al. developed a geographic information system (GIS) based spatial model for identifying suitable sites and capacities for bioethanol plants throughout the US [6]. Energy crops, switchgrass, miscanthus and corn stover, were considered as feedstock. Feedstock availability was calculated using a crop growth and production model. A 64 km radius buffer zone was used in the determination of available feedstocks. Valenti et al. also conducted a GIS-based spatial analysis for siting and sizing of potential regional biogas plants in Sicily, Italy [7]. Agricultural residues, including livestock manure, and food wastes were used as feedstock. A 45 km radius buffer zone was defined as the biogas plant service area. Spatial analysis results were used in the economic assessment of the proposed biogas plant investments. A GIS-based land suitability model was developed by Zareei for determining the suitable locations of potential biogas plants in Iran [8]. Rural household waste and livestock manure were used as feedstock in this study. The spatial density of theoretical biogas potential was determined at province scale (31 provinces) and utilized as a preference factor in the model. Sliz-Szkliniarz and Vogt conducted a GIS-based spatial analysis for the assessment of biogas potential from selected crops and livestock manure at Kujawsko-Pomorskie Voivodeship in Poland [9]. Poland set ambitious goals for increasing biogas power starting in 2010. The study aimed to provide insights into the economic feasibility of biogas plant installation, evaluate the incentives to encourage biogas development, and determine the amount of biogas feedstock within reasonable collection distances that makes the system economically sustainable. Rios and Kaltschmitt performed statistical and GIS-based spatial analyses for the calculation of electricity generation potential from biogas in Mexico [10]. Municipal solid waste, industrial and municipal wastewater, and livestock manure were utilized as feedstock. The study also aimed to identify the most promising municipalities (2454 municipalities) for electricity generation from biogas. Venier and Yabar applied consecutive GIS-based land suitability and spatial cluster analyses for the determination of biogas energy potential from cattle manure in the Buenos Aires Province of Argentina [11]. Siting and sizing of potential biogas plants were identified considering the economically feasible transportation distances. Díaz-Vázquez et al. targeted a similar goal to our study which is developing a replicable GIS-based approach to identify priority sites for biogas plants to provide an environmentally sustainable livestock manure management [12]. Similar to Venier and Yabar, Díaz-Vázquez et al. also applied consecutive GIS-based land suitability and spatial cluster analyses. Priority sites were identified based on clusters of nitrogen and phosphorous recovery and energy generation from livestock manure were identified in the Jalisco State of Mexico.

Investigation of energy potentials from livestock manure in Turkey gained attention after the increase of feed-in tariff for renewable energy in 2011. Ekinci et al., and Avcioğlu and Türker conducted one of the first studies on this subject [13,14]. They estimated province scale biogas potentials from 2009 livestock manure data. Karaca, and Ersoy and Ugurlu investigated spatial distribution and magnitude of energy potentials from poultry and dairy cattle manure, and all livestock manure, respectively [15,16]. Both studies conducted GIS-based analyses using 2015 livestock data at province scale (81 provinces) in Turkey. Melikoglu and Menekse on the other hand forecasted Turkey's energy generation potential from sheep and cattle manure regardless of spatial distribution from 2018 to 2026 [17]. They utilized the historical data on per capita milk production and meat consumption for the estimation of livestock population. The literature reviewed above is summarized in Table 1.

In the previous studies, biogas potential from livestock manure was often investigated spatially. Temporal variability in livestock manure was not taken into account. In this study, each spatial unit was considered with its temporal variations by creating a set of space-time cubes over the study area and advanced statistical analyses were performed, besides mapping the spatial distribution of energy/resource potential as in the previous studies. In this aspect, this study presents a unique and replicable GIS-based spatiotemporal method to determine emerging hot spots and power capacities for new biogas plants and capacity expansion for the existing plants. The method aids in decision-making process of environmentally and economically sustainable livestock manure management planning and biogas investors to direct their investments into profitable locations. Another distinction of the present study is to have the smallest spatial scale compared to the previous studies conducted in Turkey. Analyses were conducted at the district scale (970 districts) in this study, while province scale (81 provinces) was used in the previous studies. Space-time cube based advanced statistical analyses used in the spatiotemporal method distinct our study from the previous works. In addition, the detailed spatial scale highlights our study as the most detailed investigation of biogas potential from livestock manure in Turkey.

2. Materials and methods

The methodology of this study consists of four consecutive steps: data collection for the calculation of biogas production from livestock manure (1), geodatabase design and generation for spatiotemporal analyses (2), spatiotemporal pattern mining of biogas potential from livestock manure (3), and economic assessment of potential biogas plants (4). The step-by-step methodology is demonstrated in Fig. 1.

2.1. Study area

Turkey is located between the Asian and European continents with a 780,043 km^2 surface area. There are 81 provinces and 970 districts in Turkey [18]. The area of districts ranges between 4036 km^2 and 7 km^2, while the average district area is approximately 802 km^2 [19]. According to the 2020 population census, Turkey's population is approximately 83.6 million. The population is significantly high in the northwest of the country, which causes high urbanization, while the northeast region is the least populated [20]. Turkey has the highest livestock population in Europe with 17.221 million bovine animals, 33.678 million sheep and 10.635 million goats, and it comes second in poultry population [21]. Bovine animal, sheep and goat, and poultry population increased by 23%, 26% and 29% between the spatiotemporal analysis time range of the present study, 2013 and 2019, respectively [22]. However, Turkey, with only 72 active biogas plants (63 utilize livestock manure as feedstock), is listed towards the end of the list of number of biogas plants in Europe [2,3]. The plant power capacities range between 0.24 and 15.25 MWe, while the average capacity is 3.71

Table 1
Studies on biogas potential, biomass type, analysis approach, and application area.

Reference	Biomass type	Approach	Application area
Yalcinkaya [5]	Livestock manure and OFMSW	GIS-based spatial analysis	Izmir, Turkey
Sharma et al. [6]	Energy crops, switchgrass, miscanthus, and corn stover	GIS-based spatial analysis	US
Valenti et al. [7]	Agricultural residues, livestock manure, and food wastes	GIS-based spatial analysis	Sicily, Italy
Zareei [8]	Rural household waste and livestock manure	GIS-based spatial analysis	Iran
Sliz-Szkliniarz and Vogt [9]	Selected crops and livestock manure	GIS-based spatial analysis	Kujawsko-Pomorskie Voivodeship, Poland
Rios and Kaltschmitt [10]	Municipal solid waste, industrial and municipal wastewater, and livestock manure	GIS-based spatial analysis	Mexico
Venier and Yabar [11]	Cattle manure	GIS-based spatial analysis	Buenos Aires Province, Argentina
Díaz-Vázquez et al. [12]	Livestock manure	GIS-based spatial analysis	Jalisco State, Mexico
Ekinci et al. [13]	Livestock manure	Spatial Analysis, Table calculation	Region scale, Turkey
Avcioğlu and Türker [14]	Livestock manure	Spatial Analysis, Table calculation	Province scale, Turkey
Karaca [15]	Poultry and dairy cattle manure	GIS-based spatial analysis	Province scale, Turkey
Ersoy and Ugurlu [16]	Livestock manure	GIS-based spatial analysis	Province scale, Turkey
Melikoglu and Menekse [17]	Sheep and cattle manure	Temporal Analysis, Semi empirical models	Turkey

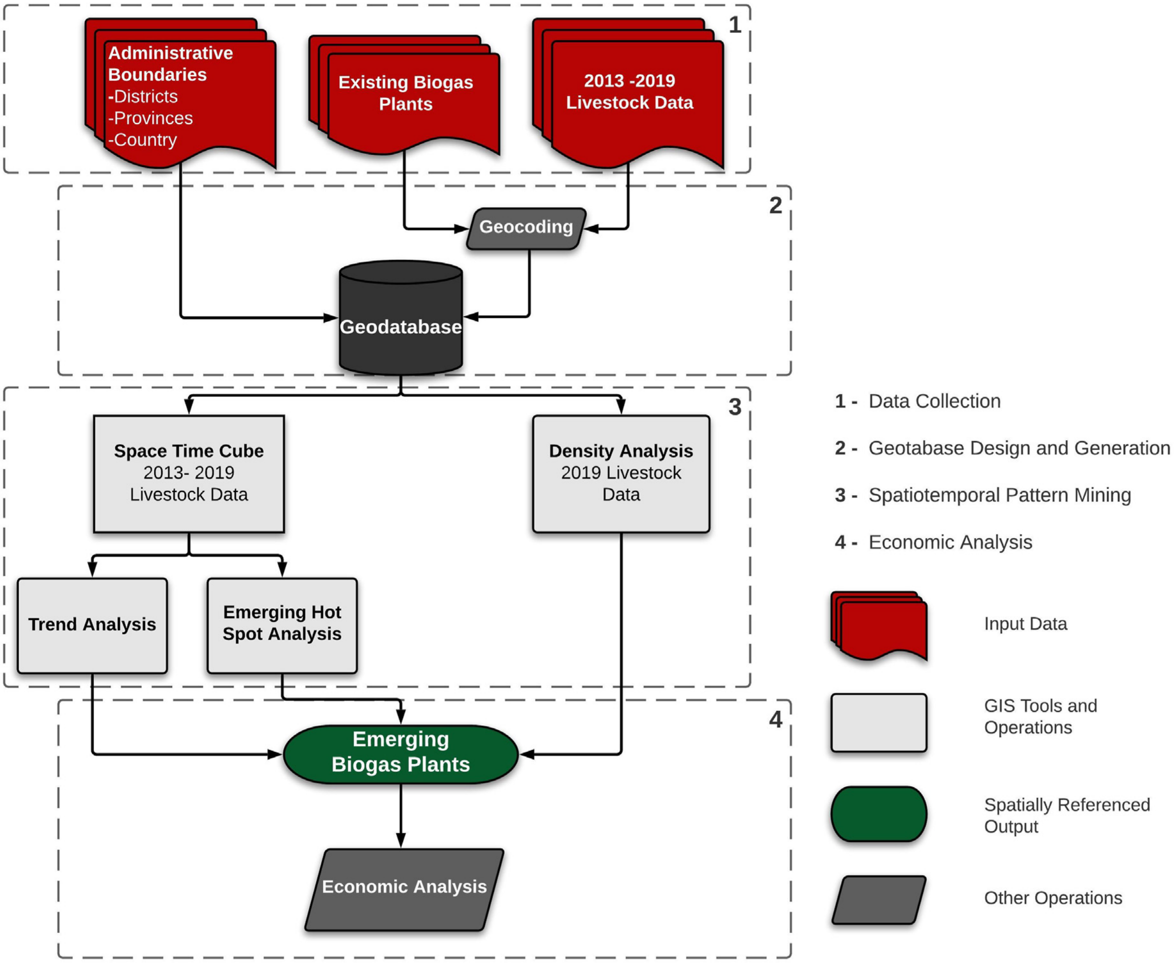

Fig. 1. Demonstration of the step-by-step methodology.

MWe. The study area and the existing biogas plants utilizing livestock manure are shown in Fig. 2.

2.2. Data collection, and geodatabase design and generation

The first step of the methodology is data collection and geodatabase design and generation. District level livestock and poultry population data were obtained from the Turkish Statistical Institute for 7 years, between 2013 and 2019 [22]. The data was obtained in 63 different categories based on type, age, and gender of animals in tabular format. Livestock categories and their weekly manure production rates are presented in Table A1 [23]. Livestock manure represents manure from bovine animals, sheep and goats, and poultry in this study. Livestock manure production, biogas

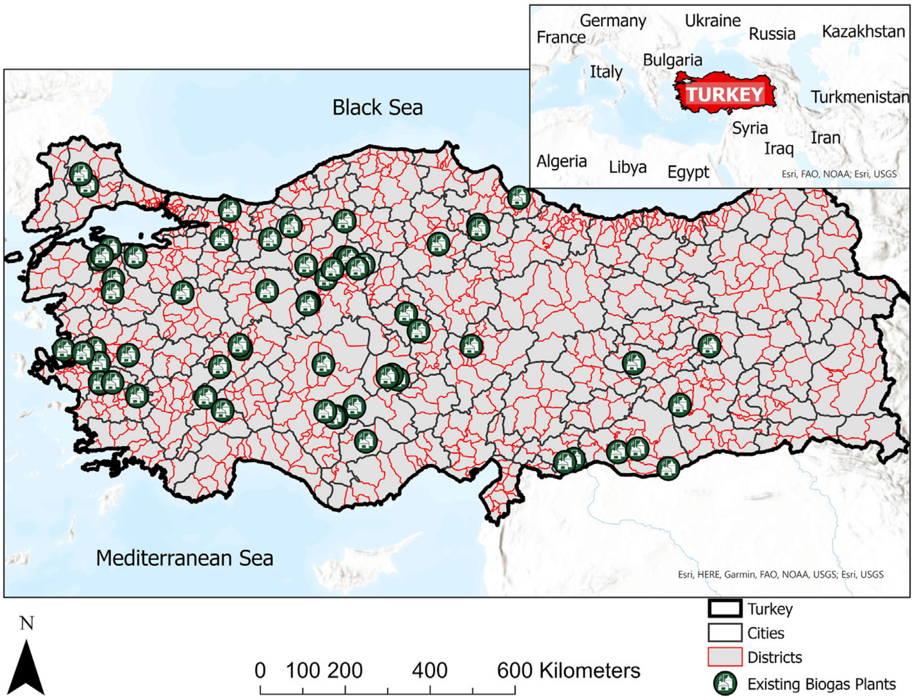

Fig. 2. The study area and existing biogas plants.

production, energy generation and power capacities were calculated from livestock population data, as explained in the following section. Administrative boundaries at nation, province and district levels were obtained from the General Directorate of Mapping in vector format [24]. Tabular livestock data was converted into georeferenced data by associating each district with its livestock population, manure production, biogas production, energy generation and power capacities. 13 time steps were established for each district (2 periods for each year). Existing biogas plants and their locations were gathered from the Energy Market Regulatory Authority [3]. The ArcGIS Pro software version 2.7 was used to create the geodatabase, process data, create a space-time cube, and perform trend analysis, emerging hot spot analysis and density analysis. All data were transformed to World Geodetic System 1984 (WGS 1984) Universal Traverse Mercator (UTM) Zone 35 projected coordinate system to preserve the integrity of the spatiotemporal analyses.

2.3. Spatiotemporal pattern mining of energy potential from livestock manure

2.3.1. Energy potential from livestock manure

Equations and parameters to estimate energy potentials were adopted from Yalcinkaya [5]. Energy potential from livestock manure was calculated using Eq. (1), as follows:

$$Energy\ Potential_{LM} = \sum_{i=1}^{n}\sum_{j=1}^{m} A_{ij} \times H_{ij} \times S_{TS_j} \times M_{LM_j} \times \alpha_j \times D \times Q_M \times \eta \times \frac{1}{7}\frac{week}{day} \qquad (1)$$

where A is the number of livestock; H (m^3/week) represents the amount of the livestock manure in volume per week; i and j are indices for district and livestock type, respectively; n is the total number of districts; m is the total number of livestock type; S_{TS} is the total solid content (kg TS/kg manure); M_{LM} indicates the methane generation per unit of total solids (m^3 CH_4/kg TS); D is the average manure density (kg/m^3); α is the collectible livestock manure, Q_M is lower heating value for methane (MJ/m^3), and η is the electrical energy conversion efficiency [5]. S_{TS} and M_{LM} values vary depending on the type of livestock, therefore indexed by j. D values were reported between 1009 and 1041 kg/m^3 for bovine animals, sheep and goats, and poultry by Lorimor et al. [25]. D was taken as 1000 kg/m^3 for all livestock manure in this study. Q_M was taken as 37.2 MJ/m^3 [26]. η for electrical energy generation from biogas by internal combustion engines was reported between 38% and 46% by the manufacturer [27]. η was taken as 0.4 (40%) in this study. H_{ij} was calculated by multiplying the amount of each livestock type and weekly manure production rate reported in Table A.1 [23].

Yalcinkaya conducted field studies in Izmir, Turkey, and determined that collectible livestock manure (α) values vary depending on the scale of facilities [5]. In large industrial farms where animals are kept in closed areas, the manure collection rate is close to the theoretical level (where $\alpha = 0.99$), while most of the livestock manure cannot be collected due to the insufficient infrastructure in small enterprises. In this case, the α value is approximately 0.5 for cattle, sheep, and goats. High rates were observed ($\alpha = 0.99$) at poultry facilities which are generally well-equipped large facilities. Considering the fact that the new regulation will be in charge by the end of 2021, theoretical energy potentials with high collection rates ($\alpha = 0.99$) were also considered in the following spatiotemporal analyses. Finally, energy potentials for each district were converted into installed power capacities in MWe units. M_{LM}, $S_{TS,}$ and α values for different livestock animals are given in Table 2.

District level density analyses were conducted using the most recent livestock data (2019). Spatial distribution and magnitude of livestock manure were investigated. Density analyses were performed for both theoretical and collectible livestock manure.

2.3.2. Spatiotemporal pattern mining

The first step of spatiotemporal analyses is to create a space-time cube. A space-time cube consists of bins over constant locations. Each bin contains temporal data for those defined locations and may accumulate on top of each other for a designed time. By creating a space-time cube spatiotemporal data is stored into a netCDF data structure which allows to visualize and analyze spatiotemporal data in GIS software. In our case, there are 970 spatial variables (districts) that do not change over time and 13 temporal variables (livestock data 2 periods per year for 7 years). The number of data and statistics (sum, mean, median, minimum, maximum, and standard deviation) are calculated for every bin of the defined location cube.

Mann-Kendall trend test was used in trend analysis to determine the temporal trend of bin values at each defined location. In the Mann-Kendall trend test, bin values and their time sequence are analyzed with rank correlation. The first bin value of a defined location is compared to the second bin value. The result becomes +1 if the second bin value is larger than the first bin value. The result becomes −1 if the second bin value is smaller than the first bin value. The result becomes 0 if the first and second bin values are equal. Every bin value is compared to its successive bin value and the results are summed. If the sum is zero, which is the expected result, it means that there is no temporal trend in the variable for the defined location. To determine the statistical significance of the difference, the calculated sum and the expected sum are compared. Z-scores (standard deviation) and p-values (probability) are used to determine the statistical significance of the bin time series' trends. The trend with a small p-value is statistically significant. If the trend is increasing, it has a positive z-score, and if it is decreasing it has a negative z-score [29].

Besides trend analysis for temporal trends and density analysis for magnitude of the variable, emerging hot spot analysis was conducted to determine the locations that require the highest attention or priority in a decision-making process. Emerging hot spot analysis classifies each defined location into new, consecutive, intensifying, persistent, diminishing, sporadic, oscillating, and historical hot and cold spots based on patterns detected over time and space. It might also detect no pattern. The space-time cube in netCDF data structure is used as input for the emerging hot spot analysis. Emerging hot spot analysis performs two consecutive statistical analyses for each bin: Getis-Ord Gi* statistic for spatial evaluation [30], and Mann-Kendall trend test for temporal analysis. First, Getis-Ord Gi* statistic is calculated for each bin to determine the intensity of spatial clusters for high and low values within a given neighborhood distance. Every bin is compared with its neighboring bins to assess whether its value contributes to a statistically significant hot or cold spot or not. A high bin value may not be a statistically significant hot spot unless it is surrounded by bins, which also have high values. Following the Getis-Ord Gi* statistic calculations, the Mann-Kendall trend test is performed to categorize these hot and cold spots within a given neighborhood time step as new, consecutive, intensifying, persistent, diminishing, sporadic, oscillating or historical [31]. Two parameters, namely, neighborhood time step and neighborhood distance are inputted to describe the neighborhood of each bin [32]. A fixed neighborhood distance of 10 km and 70 km, and a time step of 1 (the current and preceding periods) were set in this study. The impacts of selected neighborhood distances were evaluated in the results and discussion section.

Table 2
Methane generation per unit of total solids (M_{LM}), total solids content (S_{TS}), and collectible part of the total livestock manure (α) for different livestock types.

Livestock	M_{LM}[a] (m^3 CH$_4$/kg TS)	S_{TS}[a] (kg TS/kg manure)	α
Dairy Cattle >24 months	0.14	0.11	0.5[c]
Cattle >24 months	0.14	0.11	0.5[c]
Cattle 12–14 months	0.14	0.15	0.5[c]
Cattle <12 months	0.14	0.15	0.5[c]
Sheep	0.11	0.23	0.5[b]
Goat	0.07	0.32	0.5[b]
Poultry	0.19	0.16	0.99[c]

[a] [26].
[b] [28].
[c] [5].

2.4. Economic assessment

An economic assessment was conducted to evaluate the economic feasibility of biogas plants installation at the emerging hot spots. The economic assessment was conducted based on costs and revenues. District level central biogas plants were considered in the economic assessment. Costs include investment costs (I), and operation and maintenance (O&M) costs, while electricity generation from biogas was considered as the revenue.

The unit costs were taken from the International Renewable Energy Agency reports [4]. The investment cost of biogas plants was reported between 2574 and 6104 $/kW. The average reported value of 4339 $/kW was used in Equation (2). The investment cost includes feedstock handling and preparation machinery, construction, engineering, equipment, and planning costs. Operation and maintenance costs were classified into variable and fixed costs. Fixed O&M consists of scheduled maintenance, labor, insurance, and routine component/equipment replacement. 2.1–7% of investment cost was reported as the annual fixed O&M costs. Variable O&M costs are estimated based on the energy generation rate of the plant and were reported as 4.2 $ per MWh energy generation. Variable O&M costs include incremental servicing, unplanned maintenance, and equipment replacement costs. The installed capacity (x_p) and energy generation (x_e) were calculated using the most recent livestock data (2019) for each district in the density analysis. The cost equations are given below [4].

$$Investment\ cost,\ I\,(\$) = 4339x_p\,(x_p, kW) \tag{2}$$

$$O\&M\ cost\left(\frac{\$}{y}\right) = 0.045\,I + 4.2\,x_e(x_e, MWh) \tag{3}$$

The annual cost (T_c) of a biogas plant was estimated using Eq. (4):

$$T_c = Ia + O\&M \tag{4}$$

$$a = \frac{i\,(1+i)^T}{((1+i)^T - 1)}$$

where T_C indicates the annual total cost ($/y); α indicates the annuitization co-efficient; I represents the investment cost ($); O&M represents operation and maintenance costs ($/y); i stands for the discount rate; T indicates the lifetime of a biogas plant. A 20-year lifetime is generally considered for biogas plants [9,26,33] and a 10% discount rate was taken [5,33].

The annual revenue from the electric energy generation at a biogas plant was estimated using the following equation:

$$T_R = KF \times (1 - IT) \times P_e \times U_e \tag{5}$$

where T_R is the annual revenue collected due to electricity sale ($/y); KF indicates the capacity factor for the power plant; IT indicates the rate of internal energy consumption; P_e is the annual electricity generation of a plant (kWh/y); U_e is the unit electric sale price \$/kWh. The capacity factor (KF) and rate of internal consumption (IT) were taken as 91.3% and 5%, respectively [34]. Annual electricity generation (P_e) was calculated using the most recent livestock data (2019) for each district in the density analysis. Since energy is priced as per kWh, energy potential (MJ/d) for each district calculated using Eq. (1) converted to annual electricity production in kWh/y. The net unit revenue from electricity generation (\$/kWh) was calculated by subtracting the costs from the revenue and diving the result by the total energy generation.

3. Results and discussion

3.1. Spatiotemporal trend analyses

The spatiotemporal analyses of energy potential from livestock manure were conducted for 970 districts with 13 time steps (time steps of 6 months). Temporal trend analysis for energy potential at each district was measured using the Mann-Kendall trend test. An increasing trend was observed over the study area in general, which complies with the increase in livestock and poultry population between 2013 and 2019 as stated in the study area section. 532 districts were classified with a p-value of less than 0.1 while 529 of those are classified with a p-value less than 0.01. Low p-values indicate that rather than a random pattern, energy potentials across time exhibit a statistically significant increase for those 532 districts. Increasing trends were observed especially in the central and southeast regions of Turkey. On the other hand, 113 districts exhibited decreasing trends. In addition, no particular trend of increase or decrease was observed in 328 districts. The results of temporal trend analysis are presented in Fig. 3.

Emerging hot spot analysis considers spatial distribution, magnitude and temporal trends together; therefore, it provides better insights into the prioritization of districts for livestock manure management through biogas plants. Emerging hot spot analysis was conducted within fixed distances of 10 km and 70 km considering the transportation of livestock manure. Time step interval was defined as 1 which encompasses analysis time step and one preceding time step. The resulting emerging hot spots map indicates the districts that require priority when planning to construct new biogas plants or expand the capacity of existing biogas plants. Since the maximum district radius is approximately 35 km (if districts are assumed to have circular shapes), emerging hot spot analysis was performed with 70 km neighborhood distance at first to allow every district has at least 1 neighbor (bin). It was observed that even if a district has high energy potential, it may not be pointed as a hot spot due to the surrounding districts within 70 km distance from its center. When the emerging hot spot analysis was conducted within the 10 km distance, all districts with high energy potentials were correctly specified as hot spots. Because most of the districts were evaluated within themselves when the neighborhood distance was less than 10 km. Transportation distance between feedstock sources and potential plant sites is one of the most important factors for the economically sustainable management of livestock manure through biogas plants. It was reported that if the transportation distance between livestock manure source and biogas plant is more than 20 km, it results in a negative energy inflow/outflow ratio [35]. Even with a 5 km distance, the ratio is over 60%. This indicates that biogas plants must be located close to feedstock sources if livestock manure is the feedstock. Therefore, further analyses were conducted within a 10 km distance band.

Emerging hot spot analysis with a 10 km distance band resulted in 66 emerging hot spots (Table A.2). The only district identified as the new hot spot is located in central Turkey. This district was never classified as a hot spot except for the last time step. 24 districts were classified as intensifying hot spots. High energy potentials through ninety percent of all time steps were calculated for these districts and the intensity of energy increased in each time step. Consecutive hot spots are the most abundant hots spots with 25 districts. These districts have continuously high energy potentials over time. 8 districts were classified as persistent hot spots. They have high energy potentials over time but neither increasing nor decreasing temporal trends were observed. 7 districts were classified as sporadic hotspots. These districts have high energy potentials through less than 90% of all time steps, but never were a cold spot. The only diminishing hot spot is located in the northwest. This district has significant energy potential in each time step, but the intensity of the energy potential has been decreasing. Cold spots were observed in the metropolitan areas of the northwest region (in Istanbul) as a result of urbanization. The emerging hot spots are presented in Fig. 4.

3.2. Density analyses

District level density analyses were conducted to analyze spatial distribution and magnitude of theoretical and collectible installed power capacity (MWe) from livestock manure using 2019 data. The total theoretical and collectible power capacity were calculated as 2269.61 MWe and 1238.57 MWe, respectively. There is an important difference between the theoretical and collectible installed power capacities due to the poor manure management. This gap is expected to be significantly reduced by the application of the new regulation. The highest power capacities were observed in the eastern, central and some western districts, where livestock and poultry populations are higher than the other regions. The highest theoretical power capacity of 22.5 MWe was calculated for the central district of the city of Aksaray, located in the central region (Table A.2). There are 3 existing biogas plants in this district with a total installed capacity of 8.67 MWe. Despite the high power capacity of the eastern region, there is not any biogas plant in this region. Another important region is the southeast of Turkey, where power capacities range between 4 MWe and 22 MWe. There are only a few biogas plants in this region. Similarly, a great part of the south and central regions show high rates of power capacities. The third highest power capacity of 17 MWe was calculated for one of the western districts, Odemis (city of Izmir, Table A2). An important number of the existing plants are located in the western region. The results of density analyses are presented in Fig. 5.

Karaca, and Ersoy and Ugurlu investigated spatial distribution and magnitude of energy potentials from poultry and dairy cattle manure, and all livestock manure, respectively [15,16]. Both studies conducted GIS-based analyses using 2015 livestock data at province scale (81 provinces) in Turkey. Although similarities occur in the spatial distribution and magnitude of energy potentials, major differences were observed between our study and theirs due to their larger spatial scale. 5 districts on our top 10 ranked hot spots (Table A.2) were listed among the low energy potential provinces; Central District/Aksaray, Tarsus/Mersin, Central District/Igdır, Central District/Elazıg, and Central District/Nigde. Theoretical installed power capacities for these districts range from 22.54 MWe to 11.99 MWe, which should not be ignored. The main reason for this difference is that mismatched districts are located in small sized provinces. On contrary, large sized provinces, such as Erzurum and Konya, were generally classified as high energy potential provinces, although they contain some districts with very low energy potentials. In our method, a high energy potential district may not be a statistically significant hot spot unless it is surrounded by districts, which also have high values. In addition, these hot and cold spots

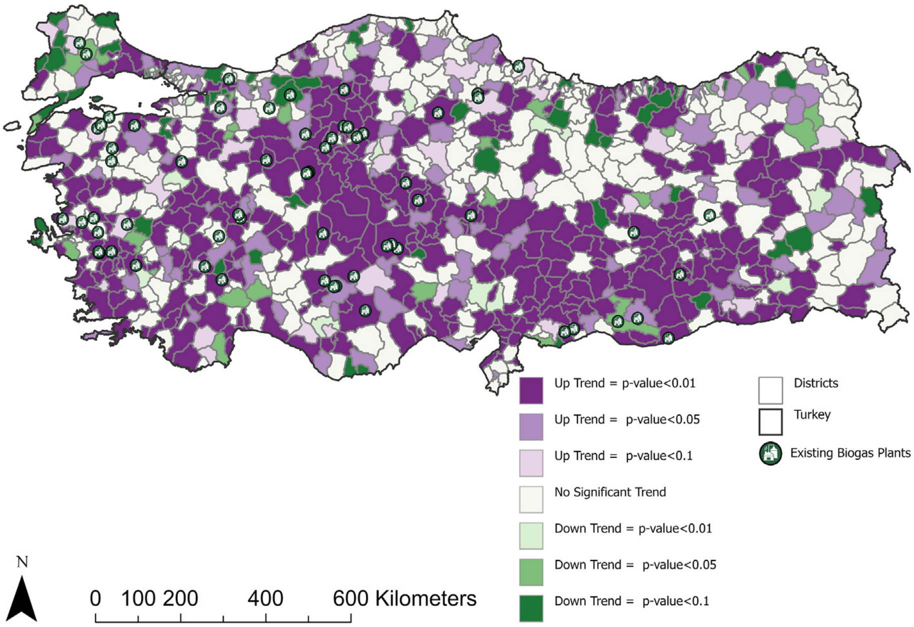

Fig. 3. Temporal trend map of energy potential from livestock manure between 2013 and 2019 with the Mann-Kendall trend test.

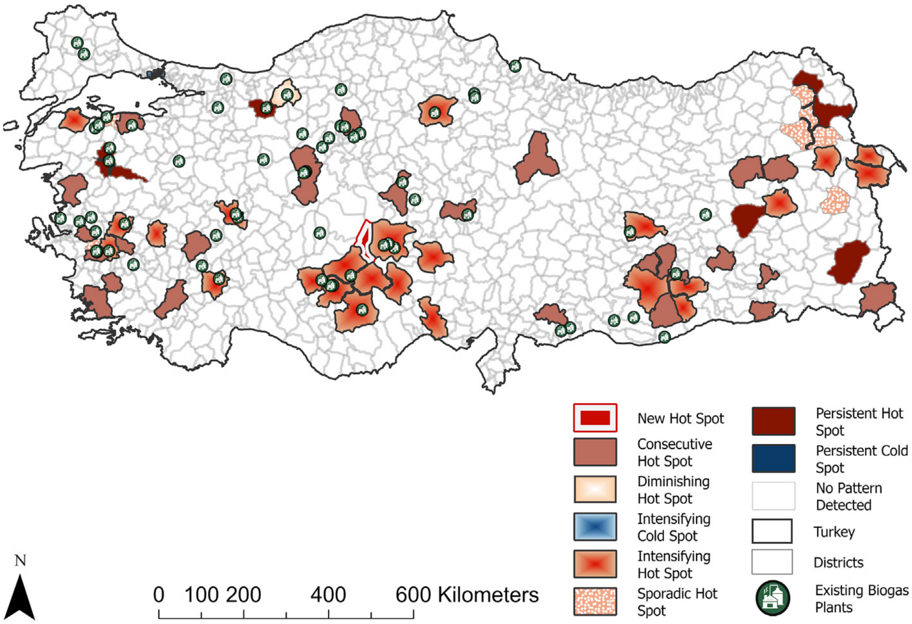

Fig. 4. Emerging hot spots for energy generation from livestock manure with 10 km distance band and 1 time step.

are further evaluated within a given time step and temporally categorized as new, consecutive, intensifying, persistent, diminishing, sporadic, oscillating or historical. Considering the transportation costs, knowing where the resources are located and their spatiotemporal trends are important in planning biogas investments. Therefore, the smaller the analysis scale the more precise the results.

3.3. Opportunity analysis

Districts defined as emerging hot spots along with their cities, power capacity rankings, installed power capacities, services area radiuses, existing biogas plant capacities, capacity expansions for the existing plants, and the number of existing plants are listed in Table A2. These districts emerge as priority locations in terms of livestock manure management investments via biogas plants considering their energy potential. These results do not mean that districts not defined as hot spots do not have enough feedstock for constructing new biogas plants. It means that the resulting hot spot districts are prominent among others considering the magnitude and temporal variation in energy potentials. The results may be used to determine the 1st phase of biogas plant installation sites. The same analyses may be performed consecutively by excluding the previous hot spots to determine the next phases.

66 districts were defined as emerging hot spots which are listed among the 72 highest power capacity districts. Theoretical power

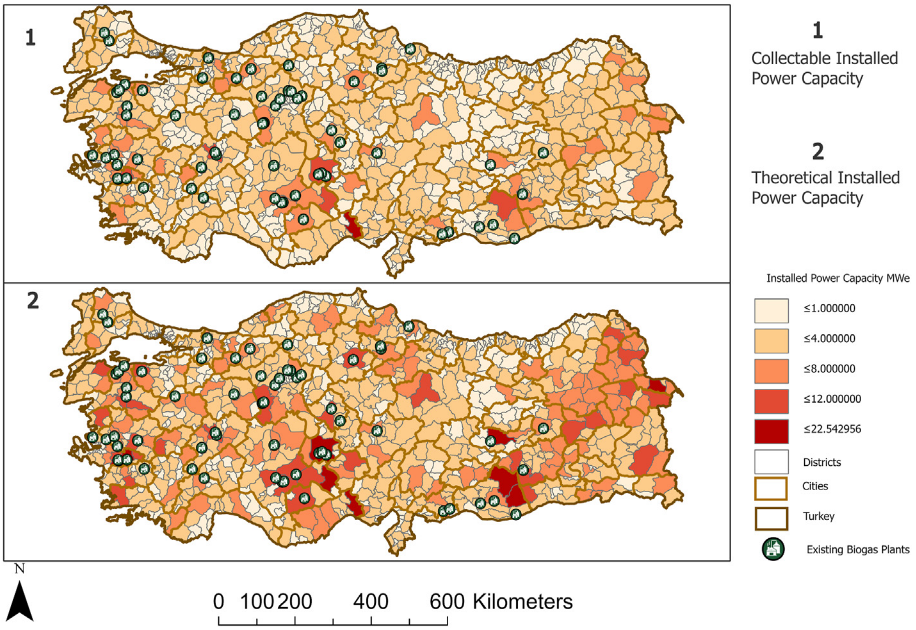

Fig. 5. Theoretical and collectible installed power capacities and existing biogas plants.

capacities of these 66 districts range between 6.4 and 22.54 MWe. Total theoretical and calculated power capacities of these districts are 640 and 357.62 MWe, corresponding to 28% and 29% of the total power capacities, respectively. 16% (102.71 MWe) of the theoretical power capacity of the emerging hot spots is already in use by the 31 existing biogas plants. Capacity expansion can range between 0.52 and 13.87 MWe, while 2 districts have more installed power capacity than the theoretical power capacity. 43 out of 66 districts have no biogas plant, which indicates the importance of this study. Service area radiuses were calculated assuming that the districts have circular shapes. Service area radius ranges between 45.6 and 15.4 km, while the average is 29.5 km.

Another important finding is that 63 existing biogas plants are located in 52 districts and 12 of those districts have biogas plants with installed power capacities more than the district's theoretical power capacity (Table A.3). 4 of those are defined as districts with overcapacity since their existing plants only utilize livestock manure. Biogas plants in the remaining 8 districts utilize other feedstock besides livestock manure. Therefore, they can compensate the negative capacity difference with other feedstock sources.

3.4. *Impact analysis*

Turkey's electricity energy generation was 303,898 GWh in 2019. According to electricity generation statistics of the Turkish Electricity Transmission Corporation, 43.88% of the electricity was generated from renewable energy sources (including reservoir hydropower, 21.69%) and the remaining %56.1 was from fossil fuels [36]. As a result of the high energy demands, a significant part of the energy is imported from external suppliers. Turkey's current energy policy aims to decrease this dependency and increase the amount of renewable energy generation. The government guarantees purchase of electricity generated from renewable sources for 10 years with constant feed-in tariffs (8.6 cents/kWh for biomass) [3]. Annual theoretical and collectible energy generation from livestock manure at the emerging hot spots were calculated as 4849.78 GWh and 2714.1 GWh in this study, respectively. The theoretical and collectible energy from livestock manure at the hot spots corresponds to 1.5% and 0.89% of the total energy generation in Turkey, respectively. Management of livestock manure through biogas plants can help reduce the energy dependence of Turkey and use of fossil fuels, while providing environmentally sustainable livestock manure management.

The economic feasibility of installation of biogas plants at the emerging hotspots was evaluated through the comparison of the unit cost of electricity generation and revenues. The transportation of livestock manure from livestock facilities to biogas was assumed to be conducted by the producer at their own expense. The total cost of 4849.78 GWh electricity generation from livestock manure was calculated as 450,440,152 $/year which equals to 0.093 $/kWh unit cost of electricity generation. Total revenue, on the other hand, was calculated as 359,052,224 $/year and corresponds to 0.07 $/kWh unit revenue. Annual deficit is calculated as 91 million $ with the existing feed-in tariff. Turkish Association of Electricity Producers suggested a minimum feed-in tariff of 12.2 cents/kWh for biogas plants utilizing agricultural waste including livestock manure and extension of the existing 10-year purchase guarantee [34]. On the contrary, the previous 13.3 cents/kWh feed-in tariff was reduced to 8.6 cents/kWh in 2021, and the 10-year purchase guarantee did not change. It can be concluded that the existing feed-in tariff for biomass based renewable energy fails to satisfy the investors. The economic downsides along with the lack of regulation in livestock manure management may have made energy generation from livestock manure unfavorable.

4. Conclusions

The spatiotemporal analysis performed in this study involves Mann-Kendall trend test and Getis-Ord Gi* statistic. These statistical calculations have been performed in various study fields for years for similar purposes. They were used together in GIS environment to develop a spatiotemporal model for determining emerging hot spots and power capacities for new biogas plants and capacity expansion for the existing plants for the first time in this study. The method was conducted to analyze energy production from livestock manure at district level in Turkey between 2013 and

2019. This study calculated the energy potential from livestock manure in Turkey at the smallest spatial scale ever. 66 districts were determined as emerging hot spots that had high power capacities. 43 out of 66 districts have no biogas plants. The total theoretical power capacity was calculated as 640 MWe. These hot spots were specified as districts with high priority for the installation of new biogas plants with power capacities ranging between 6.30 MWe and 22.54 MWe. Capacity expansion was also investigated for the existing 63 biogas plants in Turkey. Capacity expansions were calculated between 0.52 and 13.87 MWe. 4 districts were determined to have existing biogas plants with more installed power capacity than the district's theoretical installed power capacity. The results indicate the need for a systematic method in planning biogas plant installations. Our method aids in decision-making process of environmentally and economically sustainable livestock manure management planning and biogas investors to direct their investments into profitable locations.

The unit cost of electricity generation from livestock manure via biogas plants was calculated as greater than the feed-in tariff paid by the government. Increasing the existing feed-in tariff and 10-year purchase guarantee to 20 years may increase biogas investments. In addition, the new regulation, which will be in practice towards the second half of 2021, may force livestock facilities to perform more environmentally sustainable manure management practices including biogas. In this case, this study can guide biogas investors and environmental agencies to prioritize the districts and make economically more sustainable choices.

CRediT authorship contribution statement

Sedat Yalcinkaya: Conceptualization, Methodology, Formal analysis, Resources, Data curation, Writing – review & editing, Visualization, Supervision, Project administration. **Yuksel Ruhbas:** Formal analysis, Data curation, Writing – original draft, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Ministry of Food Agriculture and Livestock, Sularda tarımsal faaliyetlerden kaynaklanan nitrat kirliliğinin önlenmesine yönelik i?yi tarım uygulamaları kodu tebliği. http://www.resmigazete.gov.tr/eskiler/2017/02/20170211-12.htm, 2017.

[2] European Biogas Association, EBA statistical report 2018, Brussels, www.european-biogas.eu, 2019. (Accessed 9 April 2021).

[3] Energy Market Regulatory Authority, Elektrik piyasası yenilenebilir enerji kaynakları destekleme mekanizması (YEKDEM). http://epdk.gov.tr/Detay/Icerik/3-0-0-122/yenilenebilir-enerji-kaynaklari-destekleme-mekanizmasi-yekdem, 2021. (Accessed 13 April 2021).

[4] IRENA, Renewable energy cost analysis - biomass for power generation. https://www.irena.org/publications/2012/Jun/Renewable-Energy-Cost-Analysis—Biomass-for-Power-Generation, 2012. (Accessed 26 December 2020).

[5] S. Yalcinkaya, A spatial modeling approach for siting, sizing and economic assessment of centralized biogas plants in organic waste management, J. Clean. Prod. 255 (2020) 120040, https://doi.org/10.1016/j.jclepro.2020.120040.

[6] B. Sharma, S. Birrell, F.E. Miguez, Spatial modeling framework for bioethanol plant siting and biofuel production potential in the U.S, Appl. Energy 191 (2017) 75–86, https://doi.org/10.1016/J.APENERGY.2017.01.015.

[7] F. Valenti, S.M.C. Porto, B.E. Dale, W. Liao, Spatial analysis of feedstock supply and logistics to establish regional biogas power generation: a case study in the region of Sicily, Renew. Sustain. Energy Rev. 97 (2018) 50–63, https://doi.org/10.1016/j.rser.2018.08.022.

[8] S. Zareei, Evaluation of biogas potential from livestock manures and rural wastes using GIS in Iran, Renew. Energy 118 (2018) 351–356, https://doi.org/10.1016/j.renene.2017.11.026.

[9] B. Sliz-Szkliniarz, J. Vogt, A GIS-based approach for evaluating the potential of biogas production from livestock manure and crops at a regional scale: a case study for the Kujawsko-Pomorskie Voivodeship, Renew. Sustain. Energy Rev. 16 (2012) 752–763, https://doi.org/10.1016/j.rser.2011.09.001.

[10] M. Rios, M. Kaltschmitt, Electricity generation potential from biogas produced from organic waste in Mexico, Renew. Sustain. Energy Rev. 54 (2016) 384–395, https://doi.org/10.1016/j.rser.2015.10.033.

[11] F. Venier, H. Yabar, Renewable energy recovery potential towards sustainable cattle manure management in Buenos Aires Province: site selection based on GIS spatial analysis and statistics, J. Clean. Prod. 162 (2017) 1317–1333, https://doi.org/10.1016/j.jclepro.2017.06.098.

[12] D. Díaz-Vázquez, S.C. Alvarado-Cummings, D. Meza-Rodríguez, C. Senés-Guerrero, J. de Anda, M.S. Gradilla-Hernández, Evaluation of biogas potential from livestock manures and multicriteria site selection for centralized anaerobic digester systems: the case of Jalisco, México, Sustainability 12 (2020) 3527, https://doi.org/10.3390/su12093527.

[13] K. Ekinci, R. Kulcu, D. Kaya, O. Yaldız, C. Ertekin, H.H. Ozturk, The prospective of potential biogas plants that can utilize animal manure in Turkey, Energy Explor. Exploit. 28 (2010) 187–206, https://doi.org/10.1260/0144-5987.28.3.187.

[14] A.O. Avcioğlu, U. Türker, Status and potential of biogas energy from animal wastes in Turkey, Renew. Sustain. Energy Rev. 16 (2012) 1557–1561, https://doi.org/10.1016/j.rser.2011.11.006.

[15] C. Karaca, Determination of biogas production potential from animal manure and GHG emission abatement in Turkey, Int. J. Agric. Biol. Eng. 11 (2018), https://doi.org/10.25165/j.ijabe.20181103.3445.

[16] E. Ersoy, A. Ugurlu, The potential of Turkey's province-based livestock sector to mitigate GHG emissions through biogas production, J. Environ. Manag. 255 (2020), https://doi.org/10.1016/j.jenvman.2019.109858.

[17] M. Melikoglu, Z.K. Menekse, Forecasting Turkey's Cattle and Sheep Manure Based Biomethane Potentials till 2026, vol. 132, Biomass and Bioenergy, 2020, https://doi.org/10.1016/j.biombioe.2019.105440.

[18] Ministry of Interior, Turkey administrative divisions information system. https://www.e-icisleri.gov.tr/Anasayfa/MulkiIdariBolumleri.aspx, 2020. (Accessed 29 April 2020).

[19] General directorate of mapping, i?l ve i?lçe yüz ölçümleri. https://www.harita.gov.tr/urun/il-ve-ilce-yuzolcumleri/176, 2014. (Accessed 26 May 2021).

[20] Turkish Statistical Institute, Data Portal for Statistics - Population and Demography, Turkish Stat. Inst., 2021. https://data.tuik.gov.tr/Kategori/GetKategori?p=nufus-ve-demografi-109&dil=1. (Accessed 1 February 2021).

[21] Eurostat, Agricultural production - livestock and meat - statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agricultural_production_-_livestock_and_meat#Poultry, 2020. (Accessed 12 April 2021).

[22] Turkish Statistical Institute, Hayvancılık istatistikleri, Turkish stat. Inst.. https://biruni.tuik.gov.tr/medas/?kn=101&locale=tr, 2020. (Accessed 26 March 2021).

[23] Ministry of Food Agriculture and Livestock, Sularda tarımsal faaliyetlerden kaynaklanan nitrat kirliliğinin önlenmesine yönelik i?yi tarım uygulamaları kodu tebliği-ekler. http://www.resmigazete.gov.tr/eskiler/2017/02/20170211-12.htm, 2017.

[24] General Directorate of Mapping, Türkiye Mülki İdare Sınırları. https://www.harita.gov.tr/urun/turkiye-mulki-idare-sinirlari/232, 2021. (Accessed 1 October 2021).

[25] J. Lorimor, W. Powers, A. Sutton, Manure Characteristics, 2004.

[26] A. Gómez, J. Zubizarreta, M. Rodrigues, C. Dopazo, N. Fueyo, Potential and cost of electricity generation from human and animal waste in Spain, Renew. Energy 35 (2010) 498–505, https://doi.org/10.1016/j.renene.2009.07.027.

[27] General Electric, Jenbacher reciprocating gas engines | GE power, in: https://www.gepower.com/gas/reciprocating-engines/jenbacher, 2018. (Accessed 17 August 2018).

[28] DBFZ - Deutsches Biomasse Forschungs Zentrum gemeinnützige GmbH Torgauer Straße, Türkiye'de Biyogaz yatırımları i?çin geçerli koşulların ve potansiyelin değerlendirilmesi. http://www.biyogaz.web.tr/files/docs/dbfz_turkiye_biyogaz_potansiyel_raporu.pdf, 2011, 1-148.

[29] ESRI, How create space time cube works—ArcGIS Pro | documentation. https://pro.arcgis.com/en/pro-app/latest/tool-reference/space-time-pattern-mining/learnmorecreatecube.htm, 2021. (Accessed 10 April 2021).

[30] ESRI, How hot spot analysis (Getis-Ord Gi*) works—ArcGIS Pro | documentation, ESRI. https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-statistics/h-how-hot-spot-analysis-getis-ord-gi-spatial-stati.htm, 2021. (Accessed 16 November 2021).

[31] ESRI, Emerging hot spot analysis (space time pattern mining)—ArcGIS Pro | documentation. https://pro.arcgis.com/en/pro-app/latest/tool-reference/space-time-pattern-mining/emerginghotspots.htm, 2021. (Accessed 11 April 2021).

[32] ESRI, How emerging hot spot analysis works—ArcGIS Pro | documentation.

https://pro.arcgis.com/en/pro-app/latest/tool-reference/space-time-pattern-mining/learnmoreemerging.htm, 2021. (Accessed 19 March 2021).

[33] IRENA, Renewable power generation costs in 2018. https://www.irena.org/publications/2019/May/Renewable-power-generation-costs-in-2018, 2019. (Accessed 26 December 2019).

[34] Association of Electricity Producers, 2020 sonrası YEK teşvikleri öneri raporu. http://www.eud.org.tr/wp-content/uploads/2020-sonrasi-yek-tesvikleri-oneri-raporu.pdf, 2018. (Accessed 13 April 2021).

[35] M. Pöschl, S. Ward, P. Owende, Evaluation of energy efficiency of various biogas production and utilization pathways, Appl. Energy (2010), https://doi.org/10.1016/j.apenergy.2010.05.011.

[36] Turkish Electricity Transmission Corporation, Turkish electricity generation-transmission statistics. https://www.teias.gov.tr/tr-TR/turkiye-elektrik-uretim-iletim-istatistikleri, 2020. (Accessed 24 May 2021).