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RESEARCH ARTICLE

Analysis of Grid Flexibility With Energy Storage Technologies for the Thrace Region of Türkiye

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ABSTRACT

In this paper, three scenarios are conducted by using low emission analysis platform (LEAP) which are listed as battery scenario, natural gas scenario, and nuclear scenario for the Thrace region of Türkiye, which stands out as a region with limited electricity production and where electricity demand is mostly met through transmission lines. Three scenarios are developed because of covering batteries gap analysis in three methods. Battery scenario is required to underestimate the contribution of flexibility as soon as provided to the grid in existing circumstances. Natural gas scenario is developed to understand if the current situation in the grid process like this flexibility requirement, demand will be met by natural gas and the required amount of capacity will be identified. Lastly, the nuclear and battery capacity consistence in the grid is observed at nuclear scenario by providing optimum benefits together. It has been observed that the current situation signals commissioning of additional natural gas power plants for supplying increasing demand. However, the most important solution on the long term is deploying both nuclear plants and energy storage together. Two resources combined affect has an essential contribution to the grid by providing flexibility and decreasing dependency on long transmission lines.

Index Terms—Electricity grid, energy storage technologies, flexibility

I. INTRODUCTION

Türkiye, which had reached a population of over 85 million by the end of 2022 [1], saw its gross electricity demand grow by an average of 6.5% annually between 2013 and 2022 [2]. With its developing economy, increasing population, and rising living standards, Türkiye needs more and more energy year by year. As of the end of 2022, electrical energy consumption reached over 328 billion kWh [3].

Türkiye continues to increase the proportion of renewable energy sources in the country's energy mix. The share of renewables in Türkiye's installed power reached 54% at the end of 2022 [3]. As of the end of 2022, the electricity installed power of Türkiye reached a value of 103 810 MW value [4].

The Thrace region, where 16% of Türkiye's total electricity consumption and 7% of the production is realized [5], is one of the important topics of the country's industry and trade. The security of supply should be assessed on the basis of new emerging technologies and the needs of the electricity grid.

That necessity is arising to analyze the contribution of energy storage from batteries in the electricity grid. In this paper, energy storage systems will be explained with reference to flexibility requirements and the battery storage capacity determination of Türkiye's Thrace region.

II. ENERGY STORAGE SYSTEMS

Energy storage systems are increasing their place in the electricity system and are in a promising position for the future, depending on the prevalence of use, commercial availability, growth in intermittent renewable energy production capacity, and the approaches implemented in countries. At this point, the most basic feature of energy storage systems is that they have the ability to operate bidirectionally in power systems by acting as a supply or a load depending on the situation. In addition, they provide solutions to the user at the point of need through a wide range of uses and different technologies. They can be used as an uninterruptible power supply for a certain period of time by the end user in case of interruption or malfunction in the network. They can be used by network operators to restore the network.

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It is difficult to manage the grid to handle high renewable energy penetration. The first difficulty is that wind and solar production are variable and uncertain, resulting in volatile power generation. One predominant benefit of storage is that these systems are ideal solutions to this problem and they can improve the integration and consumption of renewable energy into the grid [6].

Energy storage is useful for deferring grid investments after a certain time with the delay, making it is possible to operate existing infrastructure within safe margins. Utility companies have an opportunity to reduce the load on transmission and distribution network assets, thereby extending the useful life of existing transmission and distribution equipment. Investments in the transmission and distribution grid require intensive capital, including power transformers and high voltage line replacement. Therefore, battery energy storage is considered an alternative to new grid investment [7].

The increasing electricity generation from solar power plants causes voltage violations in low voltage grids and leads to changes in load profiles, potentially causing reversed power flows [8]. Battery energy storage technology provides a solution for regulating voltage, with a fast response time under 20 ms, which is much shorter than conventional power plants [9].

Fast dynamic response of a storage system when injecting and absorbing active power into the grid and equipped with an inverter, with reactive power and active power, can help the grid increase its transfer limits (thermal limits, stability limits, or voltage limits) in case of transmission constraints [10].

III. BATTERY CAPACITY MODELLING

A. LEAP

Low emission analysis platform (LEAP) was developed in 1980 to provide a program for long-term integrated energy planning. Low emission analysis platform presents a structure for energy data, energy balances, preparing demand and supply scenarios, and determining policies, with the properties of flexibility and a user-friendly approach. After development, LEAP turned into one of the first energy modeling programs to address challenges related to the environmental impact of energy systems. Low emission analysis platform's modeling capabilities expanded with least-cost optimization tools. It is also provided with much more powerful support for optimization modeling, by supporting solvers and through improved cost-benefit calculation capabilities [11].

Main Points

- Focused on planning in the electricity grid of the Thrace region.
- Three different scenarios were developed within the scope of the study, considering the power plants that are determined to be built in the country in the future.
- The best solution was determined to be the joint deployment of both nuclear power plants and energy storage.
- The combination of the two sources will provide flexibility and make a significant contribution to the grid.

Low emission analysis platform is created as a long-term modeling tool. The model calculations occur on an annual time-step, and the time horizon can be extended for an extensive number of years. First of all, the existing situation and historical period are mentioned as Current Accounts, in which the model is run to test its ability to replicate known statistical data, as well as to construct multiple future scenarios. In general, most studies use a forecast period of up to five decades. Low emission analysis platform includes a number of functions that make it easy to form projections. It is possible to create interpolations, step functions, and several trend forecasts. Scenarios are coherent narratives of potential future developments of an energy system. By utilizing features inside LEAP or importing files into LEAP, analysts can build and compare alternative scenarios' energy values, costs, benefits, and environmental results [11].

Optimization model of LEAP uses the next energy modeling system for optimization (NEMO), which is an open-source energy system optimization tool. It is designed to use optimization capabilities inside the program. It is possible to analyze situations in scenarios ranging from the grid integration of variable renewable energy to energy storage and climate change subjects. Next energy modeling system for optimization is utilized for capacity expansion and power development planning, energy strategies, energy non-energy comparison analysis, and decarbonization studies [11].

B. Data Requirement by LEAP

Low emission analysis platform is a general-purpose modeling program that can be used to build a wide variety of technoeconomic models for analysis. However, some parts of LEAP are optional for data entry, such as the transformation, greenhouse gas (GHG) emissions, and costing analyses. The choice is given to users to determine their output according to defined inputs. Data requirements for demand analysis depend on the approach, whether aggregated top-down data set or a disaggregated bottom-up data set. The aggregated technique involves entering sector consumption for the entire sector at once, but the disaggregated approach details how fuels are consumed in end-uses in each sub-sector of that sector. Future assumptions and policy choices should be determined, and data sets addressed accordingly.

In general, it is advised to have the most recent and updated past and projected data for modeling. General data requirements for the program can be given below [12]:

- National population
- Rates of urbanization
- Average household number
- Macroeconomic data
- GDP
- General energy data
- Current and past national energy balances with data by sector or sub-sector.
- Documents describing national energy policies and plans and GHG mitigation assessments for the country
- Energy price data
- Demand forecasting
- Activity levels which is based on energy intensity for each sector.

It is given below for the data needed to model electric generation:

- Installed capacity (MW)
- Historical generation (GWh)
- Average energy efficiencies
- Capital, variable and fixed costs for each technology
- Load shape of system
- Maximum availability percentage dispatch priority of power plants
- Feedstock fuels are the types of fuels used in power plant
- Planned entrance of power plants
- Transmission and distribution losses.

C. Thrace Region Assessment

As of the end of 2022, the electrical energy installed power value of the Thrace region is approximately 7222 MW [13]. Almost all of the electricity generation power plants with high production capacity in the region are based on natural gas, and the total installed power of these power plants reaches 5210 MW. The installed power on the basis of resources is natural gas 72.1%, wind 22.8%, and other resources 5.1%, indicating a high dependence on natural gas. Although the Thrace region accounts for approximately 16% [14] of the total electricity demand billed, its contribution to the region's electricity generation is only 8% [15].

The second source of electricity supply for the region is transmitted electricity from the grid. The year 2021 was chosen as a starting point since it was the year in history when demand was at its peak. The peak electricity consumption of the Thrace region, which includes Istanbul European Side, Kirklareli, Edirne, and Tekirdağ cities, reached 7337 MW for the summer period of the year 2021, with the highest consumption on the Istanbul/European Side [16] (Table I). The peak consumption of the region during the year is generally realized in the winter months, and the peak consumption in the summer period is very close to the winter values.

Power transfer is carried out between the Thrace region and other regions through 400 kV overhead transmission lines and submarine cable transits. There are four units of 400 kV overhead lines with a total nominal power capacity of 5600 MVA [17]. In addition to transmission lines, two submarine cables have a total 2000 MVA power capacity, and one more submarine cable construction is ongoing [18]. Power lines crossing the Thrace region are estimated to operate at a maximum total load of 3700 MVA. The thermal capacity of the lines is high enough, but the corridor is provided by four overhead lines with different cross-sections and lengths. Transmission lines could be operated at values lower than the maximum capacity in the extremely hot summer months due to seasonal conditions, changes in the system topology, different loadings, and line characteristics. Regardless of the system configuration and specific load flow in the Turkish energy system, the imbalance rate of 21% and 41% between load and generation in the west and east, respectively, is expressed as a difficult problem to manage. It is also stated that the production–consumption balance between regions has an effect on the voltage phase angle, and in this case, angular values of 10–40 degrees/s can lead to very high frequency changes of 500 mHz/s to 1 Hz/s [19].

It is observed that there is a very high relationship between economic growth and electricity demand. It is observed that the rate of increase in electricity demand realized in the negative direction in the year 2001 and in the year 2009, when economic stagnation was experienced. After the high demand growth rates of 8.4% and 9.4% recorded in 2010 and 2011, respectively, the rate of increase in electricity demand indicated a decreasing trend. In 2019, however, there was a decrease in demand. After an increase of 6.24% in 2017 and 2.52% in 2018, electricity demand decreased by 0.28% in 2019. In the year 2020, a 0.92% increase was observed, and in 2021, there was 8.74% increase in electricity demand. However, there was 1.18% decrease in 2022 compared to the previous year. In the 2000–2022 period, the annual average increase in electricity demand was 4.4%. It is predicted that the annual average electricity demand increase will be 3% according to each scenario for demand development till the year 2053 [2, 16].

The price of batteries is an important parameter for determining their capacity in the grid, and average battery prices are expected to remain elevated in 2023 at 152 USD/kWh [20]. The selected parameter for a 4-hour battery's total cost reaches 600 USD for each kWh.

Electricity demand is shown as time slices, which is a specification of LEAP. Time slices are the seasonal and time-of-day divisions into which annual energy demands can be divided. Time slices allow a detailed look at how energy demands and supplies vary compared with annual calculations. Loads might vary both by season (summer, winter, spring, and autumn) and by time of day (weekday, week night, weekend day, and weekend night) [21]. In the selected program, it has been assumed there are four seasons in the year, weekdays, and weekends. This should be done in order to optimize calculations in the model. A total of 8760 hours of the year is expressed in terms of four quarters including weekdays and weekends (Fig. 1).

TABLE I.
THRACE REGION PEAK DEMAND ASSESSMENT ON 2021

Turkey peak demand	**56.303 MW**
Thrace region peak demand	7.337 MW
Power supplied by transmission at the peak load	3700 MW
Power generation according to resources on maximum demand time	3.610 MWh (3.510 MWh natural gas, 100 MWh others)
Installed capacity according to resources	6.807 MW (5.144 MW natural gas, 1.390 MW wind, 273 MW others)

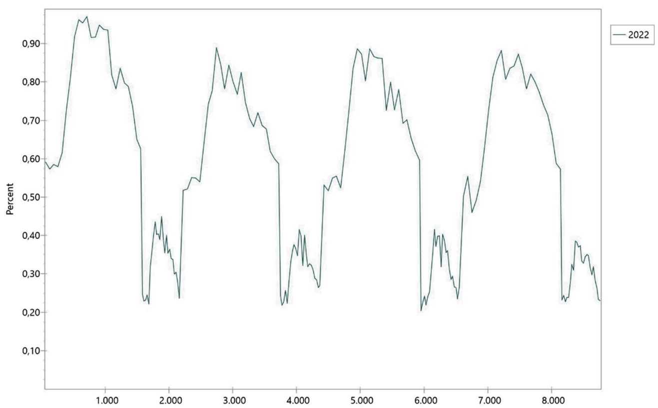

Fig. 1. Time slices of year 2022.

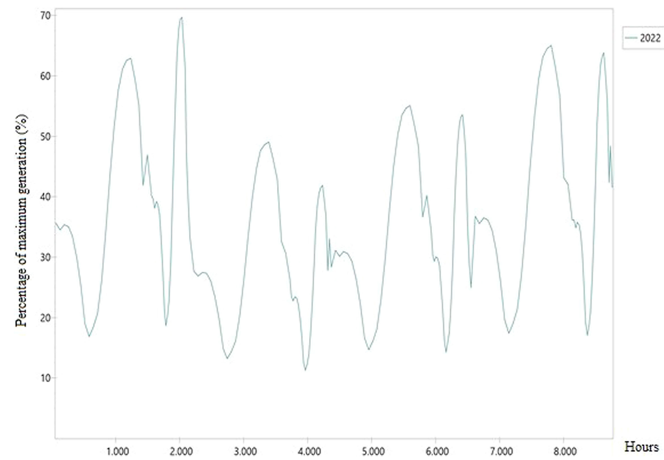

Fig. 3. Wind load scheme.

Another data entry is needed for solar and wind generation because of their typical load schemes. The model takes into consideration and optimizes future capacity and existing capacity for the generation scheme. Offshore wind capacity factors are higher than onshore wind. This means that higher energy could be generated with the same installed capacity using offshore wind compared to onshore wind. The offshore capacity factor is found by multiplying 1.3 value with the onshore value. The values are distributed for each hour using percentage values in total 8760 hours. The maximum value is taken as 1, and remaining values are calculated as a percentage of the maximum value (Figs. 2 and 3).

The maximum availability term is used to determine how many hours a power plant is available in a given year. This is expressed as a percentage value. These values are defined as follows: battery: 95%, nuclear power plant: 90%, and natural gas plant: 70%. Solar and wind values are defined according to their yearly generation patterns, which are provided according to their load schemes. The merit order dispatch term is used to simulate the dispatch of power plants to meet both the annual demand for electricity as well as the instantaneous demand for power in time slices of the year. Processes will be dispatched according to defined merit order variables, and priority is defined for renewables, nuclear, coal, natural gas, and grid electricity respectively.

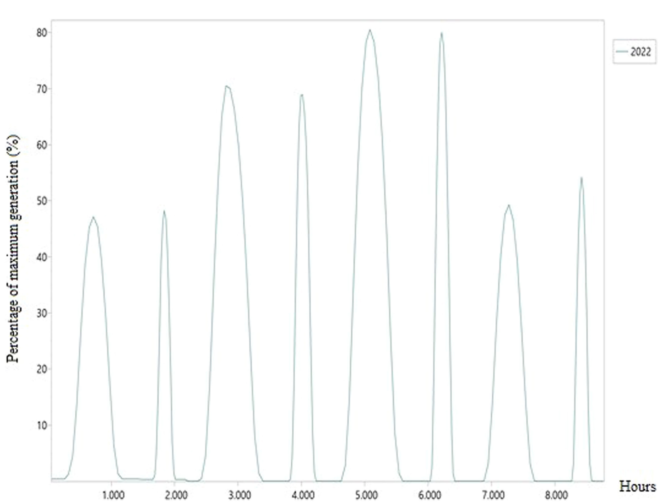

Fig. 2. Solar load scheme.

The lifetime is defined for each resource according to the amortization the capital cost and retirement. Costs are determined as 10 years for battery, 20 years for solar, 30 years for wind, and 60 years for nuclear accordingly.

Efficiency, lifetime, and cost values for power plant technology are estimated using average values from the International Energy Agency (IEA) country database [22]. The process efficiency value is required for each resource, which is the ratio of input to output for electricity generation. The efficiency of solar and wind energy systems is taken as 100%, battery's efficiency is taken as 85%, the efficiency of the natural gas combined cycle is taken as 60%, and the efficiency of existing natural gas is taken as 50%.

In the model, past generation values are required. In the year 2022, natural gas power plants generated 20 TWh, onshore wind power plants generated 5 TWh, and biomass power plants generated 1.2 TWh of electric energy [14].

Costs are divided into three categories for power plants. One of them is capital cost, which is main cost item to construct a power plant. The discount rate is taken as the interest rate, and the value is defined as 6%. Operation and maintenance costs have two parts. One of them is variable cost, and the other one is constant cost. Capital costs are determined as follows: natural gas combined power plant at 1 million USD per MW, natural gas combined cycle gas turbine at 500 000 USD per MW, solar at 500 000 USD per MW, and 1 million USD per MW for wind plant. Battery capital cost is estimated from per MWh energy capacity. The calculation is based on 2022 data, and results are belong to LEAP. The discharge duration of a battery is determined to be 4 hours and average estimated cost is taken as 0.6 million USD. Hence battery, solar, and offshore wind technology are not mature technologies, it is expected to decrease their costs in the near future according to assumptions. Battery cost is expected to decrease to its half value by the year 2050. Offshore wind cost is expected to decrease to 2.25 million USD per MW, and solar cost is expected to decrease to 0.37 million USD per MW.

Variable operation and maintenance costs occur when electricity is generated but do not exist during non-generation periods. Fuel costs are also included in this cost type. The costs are: natural gas 220 USD per MWh and 25 USD per MWh for nuclear. Fixed operation and maintenance costs are: natural gas plant 0.025 USD per MW, solar 0.016 USD per MW, wind 0.02 USD per MW, and nuclear 0.16 USD per MW.

Transmission and distribution grid losses are parameters for defining the gross consumption of the electrical system. As the analysis focused on the transmission side of the system, the gross values and losses are not considered.

Power plants are taking into consideration the reserve margin for the daily production program in case they need to supply extra power when demand comes from the grid operator. This occurs when they are not operating at full load. The reserve margin is considered to be 15%. According to the determined average increase of 3% in demand, the graph given below indicates the development of demand to nearly 110 TWh in year 2053 (Fig. 4).

The model has three scenarios, which are listed as battery scenario, natural gas scenario, and nuclear scenario. Three scenarios are developed because of covering batteries gap analysis in three methods. Battery scenario is required to underestimate the contribution of flexibility as soon as provided to the grid in existing circumstances. Natural gas scenario is developed to understand if the current situation in the grid process like this flexibility requirement, demand will be met by natural gas and the required amount of capacity will be identified. Lastly, the nuclear and battery capacity consistence in the grid is observed at nuclear scenario by providing optimum benefits together. The flexibility requirement of the grid is provided with batteries, and demand is met with natural gas-powered plants (Fig. 5). Existing natural gas plants are decommissioned, and new ones are commissioned

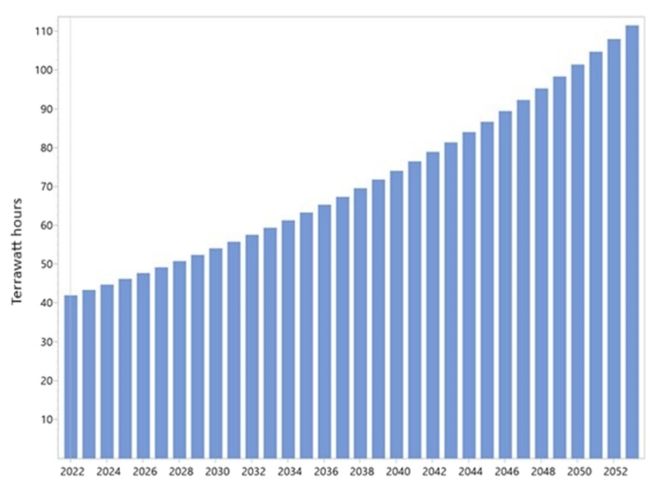

Fig. 4. Demand forecast (2023–2053).

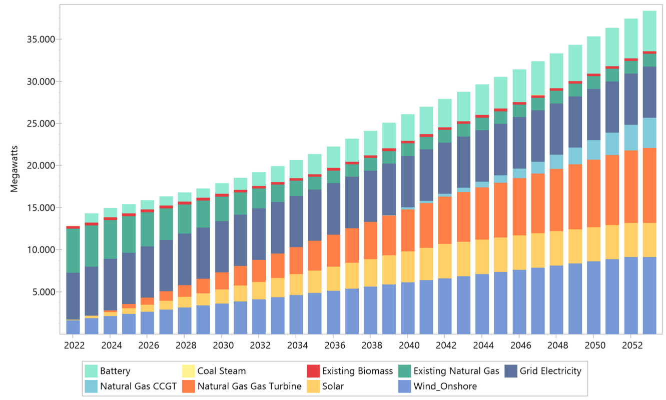

Fig. 5. Resource based installed power of battery scenario.

accordingly. Each scenario consists of renewable development for a maximum available capacity of 200 MW and wind 250 MW of wind per year.

If it is analyzed in the natural gas scenario, there has not been any battery capacity, and requirement of demand evolution and renewable capacity increase are seen in Fig. 6.

Nuclear capacity development is essential for the nuclear scenario which also determines battery capacity needs with base load. Nuclear capacity is commissioned between the years 2033 and 2036, and each year has a value of 1200 MW. With this scenario, all main types of generation resources and battery development are underestimated (Fig. 7).

The costs for each of the three scenarios are given below (Table II). However, the total cost of natural gas and battery scenarios is approximately identical. In the natural gas scenario, the capacity commissioned is 6000 MW greater than that in the battery scenario. Also, constructing a natural gas power plant requires land, cooling water, etc., and has environmental effects.

It has been observed that the most ideal grid system is realized with the entry of nuclear capacity into the grid. It is also useful for decreasing the need for interconnection lines from the grid and contributing to the demand by supplying it (Table III).

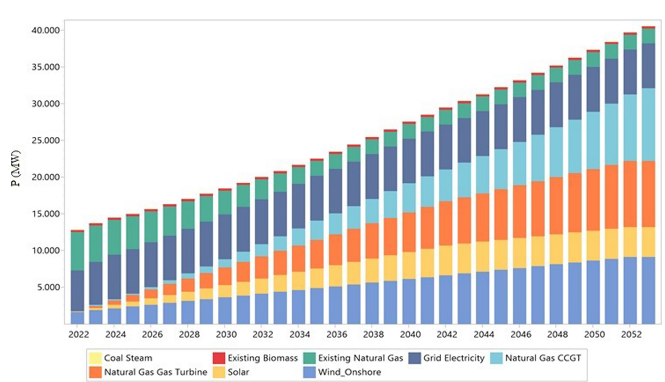

Fig. 6. Resources based ınstalled power of the natural gas scenario.

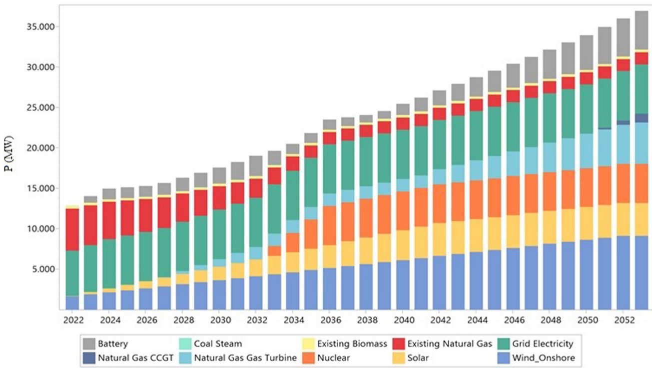

Fig. 7. Resources based installed power of the nuclear scenario.

It is observed that in the battery scenario, which does not include nuclear energy, as soon as simulation year starts, battery capacity of more than 1000 MW is commissioned. In the nuclear scenario, the development of battery capacity is dispersed over many years compared to battery scenario. Because of the entrance of nuclear capacity in the year 2033, there is no capacity commissioned for the following 6 years. After these years, with the development of renewable capacity and the met of base load of the region, battery capacity begins to increase (Fig. 8).

Fig. 9 is given for detailed analysis of the energy storage system to the grid by contributing flexibility to the electric grid for the Thrace region. There are four quarters, and according to the distribution of load, quarter one is the winter season, quarter two is the spring season, quarter three is the summer season, and quarter four is the autumn season. It is fundamentally noted that winter season is the most difficult season for the grid to manage because of the decrease in solar energy and the increased heating requirement. The contribution of the battery is evident during low demand periods and high demand periods.

There are not any battery systems commissioned in the natural gas scenario. So, it is understood that during the peak demand period, there is no option for providing flexibility to the grid. Especially during peak demand periods, load shapes and magnitudes are similar to each other as descents and ascents are identified (Fig. 10).

Load shapes of the nuclear scenario are most identical to each other in terms of their shapes; they are close to square, which means variations are not as quantifiable compared to natural gas and battery scenarios. The main reason behind that view is that nuclear energy provides a base load, and instantaneous differences are eliminated by energy storage. Compared to battery scenario, the range of battery operation for charging and discharging periods is noticeable (Fig. 11).

Analysis section is finalized by assessing each scenario. Each of the three scenarios is modeled accordingly by software LEAP [23].

IV. CONCLUSION

The energy supply to the Thrace region, where industry and population are intense and which contributes significantly in terms of

TABLE II.
TOTAL COST OF SCENARIOS

Year	Battery (Billion USD)	Natural Gas (Billion USD)	Nuclear (Billion USD)
2025	3.7	3.6	3.8
2030	4.7	4.7	4.8
2035	6.3	4.0	6.4
2040	8.6	4.7	8.7
2045	11.0	5.9	11.0
2050	14.1	8.0	14.2
2053 (Total)	263	265	170

TABLE III.
TOTAL NATURAL GAS POWER PLANT CAPACITY FOR SCENARIOS

Year	Battery Scenario	Natural Gas Scenario	Nuclear Scenario
2053	14 GW	21 GW	12 GW

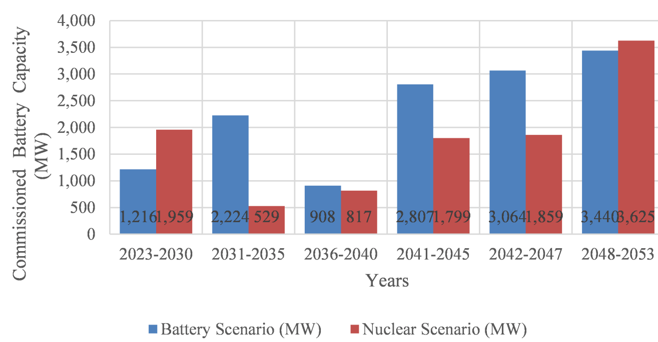

Fig. 8. Total battery capacity for scenarios between the years 2023 and 2053.

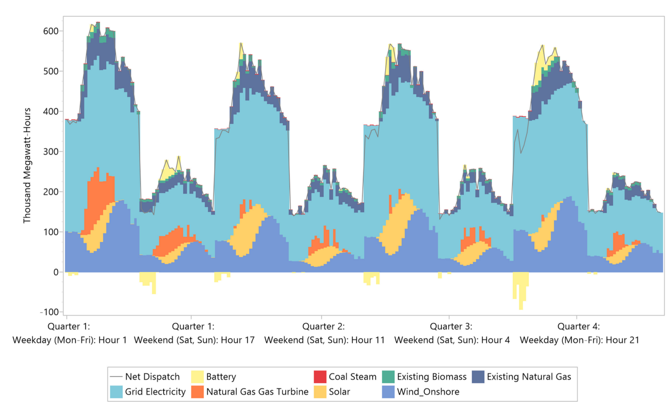

Fig. 9. Battery scenario energy generation scheme.

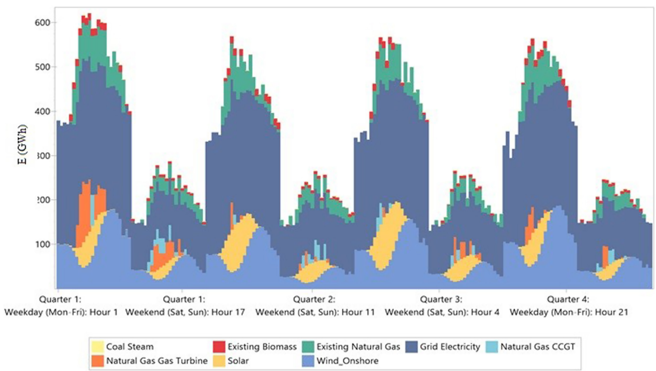

Fig. 10. Natural gas scenario energy generation scheme.

providing added value, should be handled with a special perspective. The absence of a base load power plant in the Thrace region causes serious problems in terms of the management of the transmission system. Although the electricity produced is delivered to the Thrace region with long lines and submarine cables in the grid, the establishment of a base load nuclear power plant in the region and the utilization of renewable resources are of great importance for ensuring the supply security of the region. The contribution of the energy storage system is mostly identified in the nuclear scenario when compared to the single use of the energy storage system. Energy storage systems provide the opportunity to benefit from the energy source continuously by solving the problem of the time mismatch between the period when the energy is needed and the period when the energy is produced. Renewable integration into the grid with load matching is facilitated by the help of energy storage. In the paper, scenarios are developed to determine the required storage capacity of the Thrace region. While the Thrace region has difficulties supplying its electrical demand with base load resources near the region, long transmission lines exist for transmitting electrical energy from other regions. It has been observed that the current situation signals commissioning of additional natural gas power plants for supplying increasing demand. On the other hand, adding energy storage to the grid will be beneficial for flexibility. But the most important solution on the long term is deploying both nuclear plants and energy storage together. Two resources combined affect has an essential contribution to the

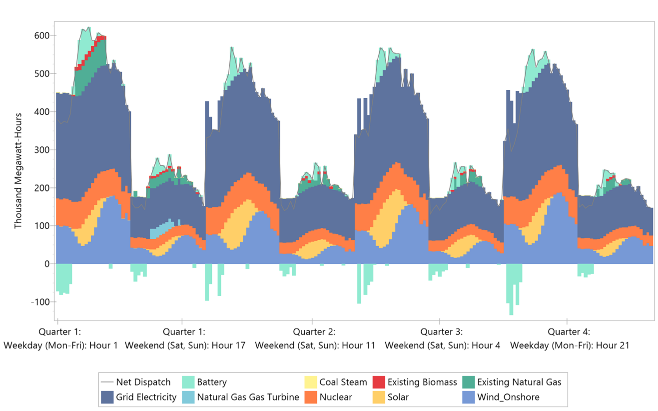

Fig. 11. Nuclear scenario energy generation scheme.

grid by providing flexibility and decreasing dependency on long transmission lines. In terms of results, it is seen that the electricity production graph contains many ups and downs in the scenario where no battery is used. With the battery scenario, a slight decrease was observed in the ups and downs graphs with the battery being activated, and the effect of the battery's contribution to flexibility was felt. In the scenario where nuclear energy and battery are used together, it was observed that the battery is activated approximately twice as much periodically compared to the battery scenario, making production more stable and reducing ups and downs, thus contributing to flexibility. In the scenario where only the battery is used, the battery's contribution was observed to be approximately 100 GWh for 3 hours, while in the scenario where nuclear energy and battery are used together, it was observed that the contribution was close to 100 GWh for 11 hours.

In the Thrace region, the need for energy storage systems has been evaluated in terms of the lost load value and the deviations in the estimated production values of the wind power plants. In order to prevent economic loss as a result of power cuts that may occur in the Thrace region, the establishment of battery-type energy storage systems, which can be put into use in the easiest and fastest time, will be a suitable solution for providing a continuous and quality electricity supply to the industrial sector. In terms of renewable energy resources, there will be benefits such as correcting the generation estimates, reducing the loading and losses of transmission lines, and regulating the frequency in terms of the grid.

Due to its sensitivity in electrical energy, the Thrace region could be chosen as a pilot region, especially in the implementation of the smart grid system, to cause interruptions and ensure the balance in production and consumption points in order to avoid restrictions. Energy storage will contribute more benefits for the management of the supply and demand sides.

Availability of Data and Materials: The data that support the findings of this study are available on request from the corresponding author.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – S.K.; Design – S.K.; Supervision – S.K.; Resources – E.S.; Materials – E.S.; Data Collection and/or Processing – E.S.; Analysis and/or Interpretation – E.S., S.K.; Literature Search – E.S.; Writing – E.S., S.K.; Critical Review – S.K.

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