# REDUCING THE COST OF ELECTRIC TRANSMISSION AND DISTRIBUTION SYSTEMS WITH WIND GENERATION BY MEANS OF ENERGY STORAGE AND DEMAND SIDE MANAGEMENT

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**REDUCING THE COST OF ELECTRIC TRANSMISSION AND DISTRIBUTION SYSTEMS WITH WIND GENERATION BY MEANS OF ENERGY STORAGE AND DEMAND SIDE MANAGEMENT**

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**I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.**

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# ABSTRACT

## REDUCING THE COST OF ELECTRIC TRANSMISSION AND DISTRIBUTION SYSTEMS WITH WIND GENERATION BY MEANS OF ENERGY STORAGE AND DEMAND SIDE MANAGEMENT

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# ÖZ

## ENERJİ DEPOLAMA VE TALEP TARAFI YÖNETİMİ VASITASIYLA RÜZGAR ENERJİSİ ÜRETİMİ BULUNAN ELEKTRİK İLETİM VE DAĞITIM SİSTEMLERİNİN MALİYETİNİN DÜŞÜRÜLMESİ

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Ocak 2018, 100 sayfa

*To my family*

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# CHAPTER 1

# INTRODUCTION

## 1.1 Motivation for the Thesis

Energy supply is one of the main interests of today's society and energy consumption is considered as an important parameter to determine the level of development of a society. World's total energy consumption has been increasing throughout the years and it is expected to rise from $549 \times 10^{24}$ Btu in 2012 to $815 \times 10^{24}$ Btu in 2040, an increase of 48% [1]. Since the industrial revolution, fossil fuels are remained as the main source of energy. However, negative impacts of these sources led the search for alternative methods to fulfill energy requirements. Climate change, which is the result of increasing greenhouse gases in the atmosphere, is the main concern about fossil fuels. Moreover, fossil fuels are non-renewable energy sources, so there is a limited supply.

Renewable energy generation has been growing rapidly, with wind power having the highest percentage. Today, wind energy is the most popular renewable energy source. In 2015, 3.7% of the global electricity was supplied by wind energy and this percentage is expected to increase for the next years [2]. Annual installations of wind energy capacity have been in excess of 50 GW for the last three years and at the end of 2016, total installed wind power capacity has reached to 487 GW. Historical development of global installed wind energy capacity over the years and forecast of wind energy capacity for the next years can be observed in Fig. 1 and Fig. 2 [3], respectively. Cumulative capacity growth rate is expected to be over 10% for the next 5 years and total wind energy capacity is expected to reach around 817 GW in 2021.

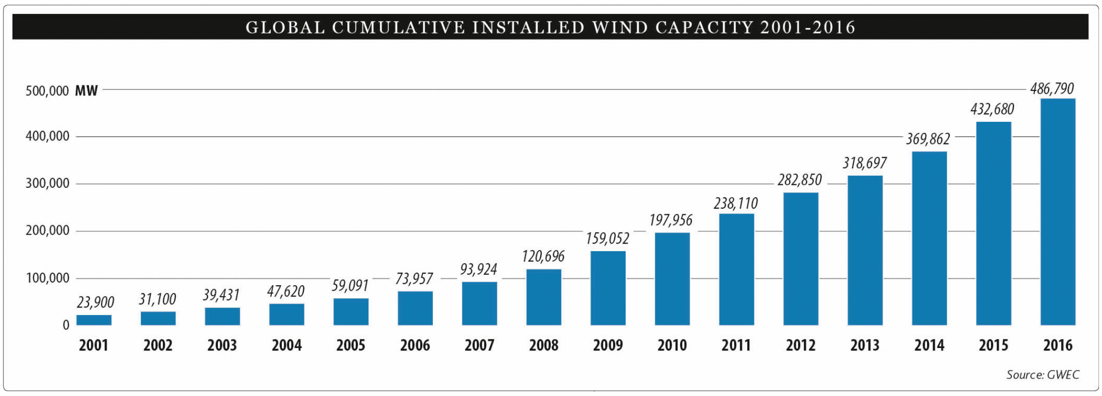


Fig. 1: Historical development of installed wind energy capacity globally [3]

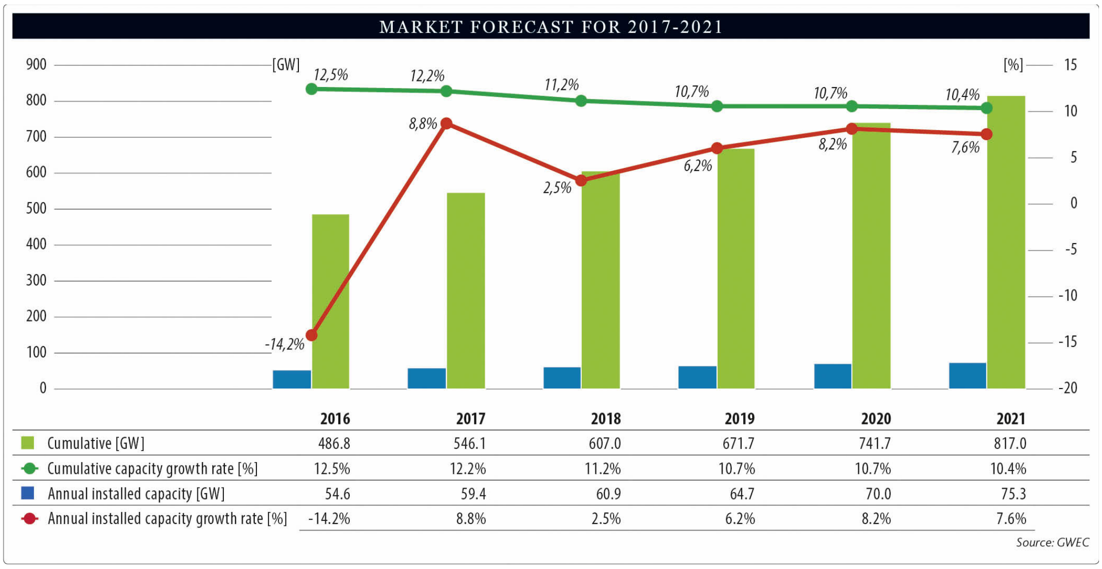


Fig. 2: Market forecast of wind energy capacity [3]

In a similar way to global development, wind energy capacity in Turkey also has been increasing over the years. Installed wind energy capacity for the last 10 years in Turkey can be observed in Fig. 3 [4]. With 1,387 MW installation in 2016, total wind capacity of Turkey is brought to 6,106 MW, which was enough to supply 7.3% of electricity demand of the country for the same year. Considering limited oil and gas reserves, Turkish government has set a national target of total wind power capacity to 20 GW by 2023 [3].

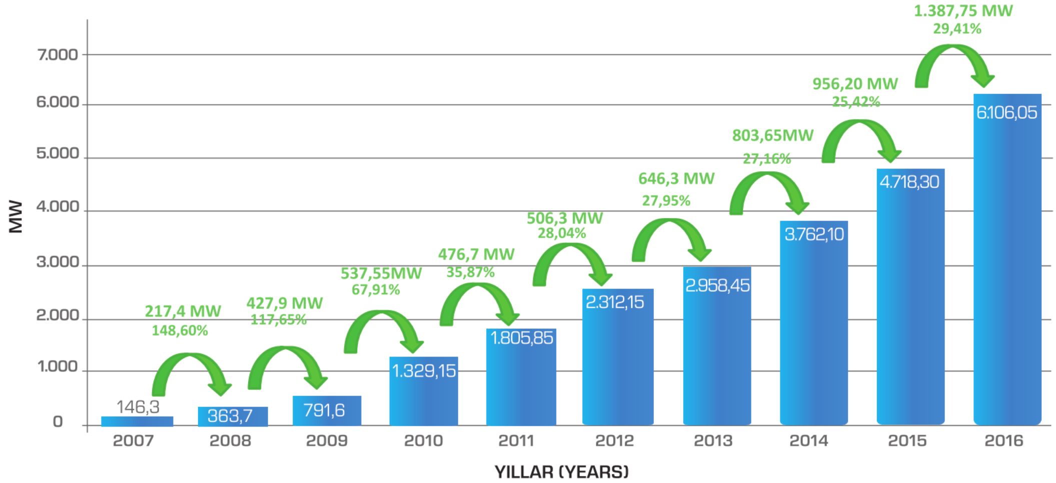


Fig. 3: Historical development of installed wind energy capacity in Turkey [4]

Power output of a wind turbine can be expressed as follows:

$$P=\frac{1}{2}\rho_{air} A v^3 C_p \tag{1.1}$$

where:

| | |
|---|---|
| $P$ | power output (W) |
| $\rho_{air}$ | air density (kg/m$^3$) |
| $A$ | swept area (m$^2$) |

$v$ wind speed (m/sec)

$C_p$ power coefficient

As it can be observed from Eq. 1.1, power output of a wind turbine is proportional to the cube of the wind speed, so even small variations of the wind speed can cause large fluctuations on the power output. In Fig. 4, 10 minutes interval power output measurements of a wind farm in Turkey is shown. Daily fluctuations of the wind power output due to variable wind speed throughout the day can be also recognized in this figure.

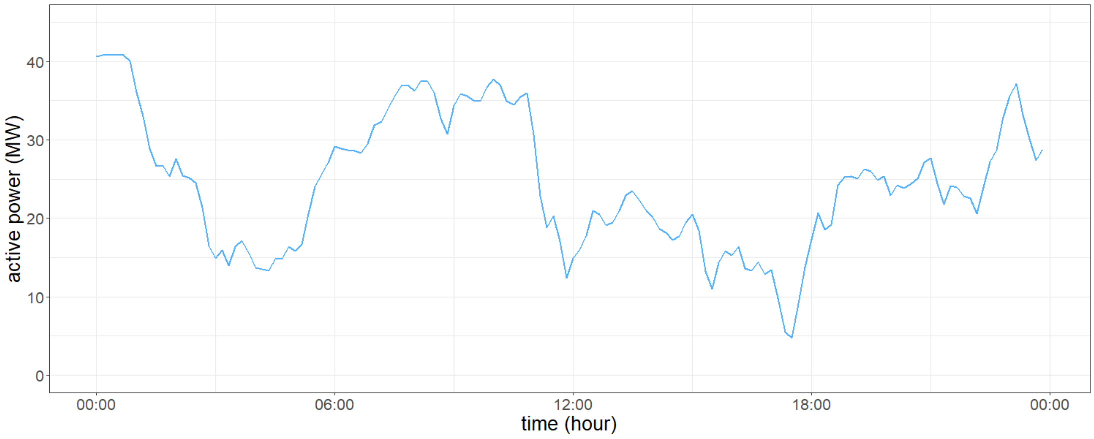


Fig. 4: Daily generation of a wind farm in Turkey

Due to intermittent nature of the wind, high level penetration of wind energy brings uncertainty and variability into power systems, therefore energy balance problem becomes harder to achieve. The impact of increasing wind power penetration level to stability and reliability of the power system can be summarized as follows [5]:

**Reliability problems:** Net-load variations can be tracked by conventional generators at low level integration of wind power to the power system. However, increasing penetration of wind energy eventually affects the system reliability as wind power output fluctuations are not controllable and generally wind generation is not related to the demand pattern, which leads an increase on the difference between peak and off-peak periods. As a result, committed conventional generators cannot compensate the sudden and large changes of wind power output.

**Stability Problems:** Synchronous generators can automatically regulate the speed governors to support frequency control. However, wind turbine generators can only provide small contributions to primary frequency support by using wind turbine level control; inertial, droop and deloading control [6]. Wind power output fluctuations will also weaken grid voltage stability due to generation and load mismatch [7].

Considering expected share of wind generation in overall electric power generation to grow significantly over the years, more flexibility in power systems will be required to handle with the negative impacts of wind power. In the near future, system flexibility needs, which has been driven by variable demand up to this day, will begin to be driven by supply variability.

For the integration of renewable energy into the power system effectively, four main options are proposed to provide flexibility to the power systems [8]:

- Dispatchable generation
- Transmission and distribution expansion
- Demand-side management
- Energy storage

## 1.2 Aims of the Thesis

With the high level penetration of wind generation, power systems are affected negatively due to intermittent nature of the wind. One of the effects of wind power integration over power systems is transmission and distribution (T&D) upgrade need over existing structures. Considering the high investment cost of upgrade, T&D upgrade deferral becomes very profitable in specific cases by increasing flexibility of the power system. Energy storage systems (ESSs) and demand-side management (DSM) are two main methods that can be integrated into power systems to supply the additional flexibility.

In this study, a system is constructed where a wind farm is connected to an organized industrial zone through distribution structure and overall system is connected to the grid through transmission structure and power overload on the transmission-side for the constructed system is analyzed for the next years. Using ESS and DSM with the proper control methods to absorb the excess power flow on the transmission structure, deferral of the transmission-side upgrade is investigated.

### 1.3 Outline of the Thesis

Outline of the thesis can be formed as follows:

- **Chapter 2** explains the flexibility concept and gives a general idea of the impact of wind generation on power systems. Literature review on energy storage systems (ESSs) and demand-side management (DSM) is also provided in this chapter.

- **Chapter 3** introduces transmission and distribution (T&D) upgrade deferral concept. Constructed scenario and selection, manipulation and implantation of the proper data are explained in this chapter. Modeling of the ESS and DSM elements are also given in this chapter with the equations used in the constructed scenario.

- **Chapter 4** illustrates the contribution of ESS and DSM to economical aspects of transmission systems. Specifications of ESS and DSM used in the study is explained and control algorithms used in the simulations are also provided in this chapter. At the end of this chapter, simulation results are given and evaluated considering the feasibility of the proposed suggestion.

- **Chapter 5** summarizes the overall work shortly. Possible future works on that subject are also discussed briefly in this chapter.

# CHAPTER 2

# PROVIDING FLEXIBILITY INTO POWER SYSTEMS

## 2.1 Introduction

The main concern about planning and operation of the power systems is maintaining the equilibrium between safety and efficiency. As the share of renewable energy over power systems increases, sustaining this equilibrium becomes a more complicated problem to be solved. In order to reduce the impacts of renewable generation on power systems, further flexibility is required. Flexibility of a power system is defined as the ability of the power system to respond to changes in demand and supply over a range of operating conditions [9]. All power systems contain some degree of flexibility, as variability and uncertainty are always an issue and systems are designed to match the supply and demand all the time. However, with the renewable generation integration into power systems, variability and uncertainty become a problem of generation-side, in addition to load-side.

For better understanding, the impact of wind generation on net-load can be observed in Fig. 5 [9]. Here, the net-load represents the demand which will be supplied by the conventional generators when the wind generation is utilized. It can be observed that wind generation leads to steeper ramps, deeper turn downs and shorter peaks on net-load, which affects the operations of conventional generators.

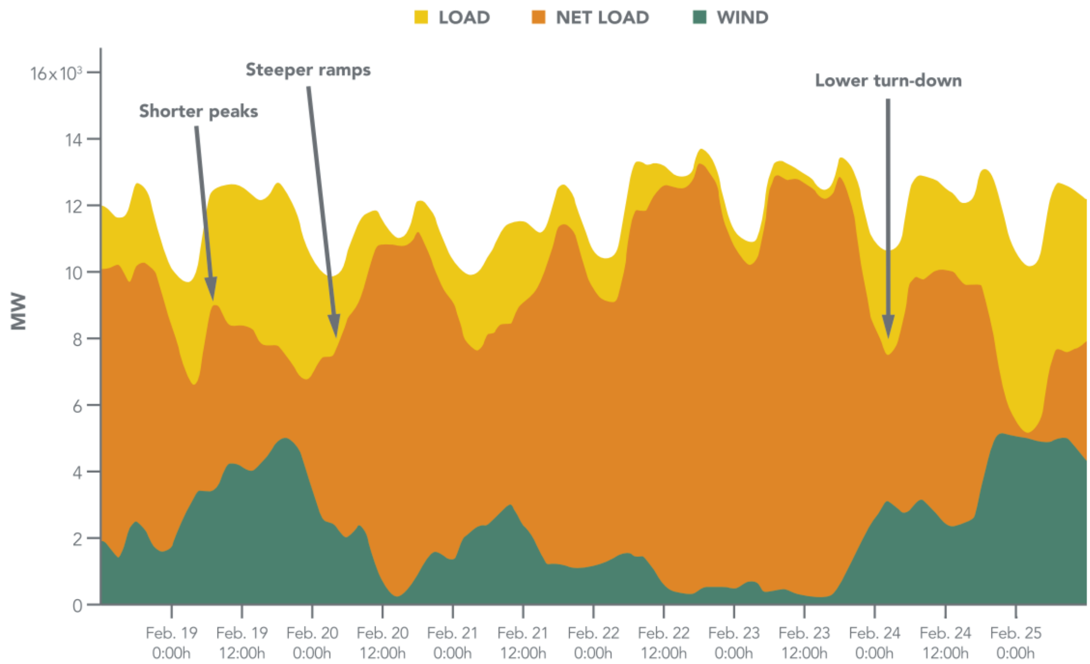


Fig. 5: Impact of wind generation on net-load [9]

In conventional power systems, generators with fast start time, high ramp-up/down rates and low minimum up/down times are used to provide flexibility. However, considering the impacts of renewable generation on power systems, alternative methods are needed to compensate emerging effects. Energy storage systems (ESSs) and demand-side management (DSM) are two main methods that can be integrated into power systems to supply additional flexibility. In this chapter, main characteristics and applications of ESSs and DSM are explained and evaluated.

## 2.2 Energy Storage Systems

In a power system, energy demand must be supplied instantaneously to preserve stability and quality of the system. In addition, scheduling of power systems with varying net-load profile decreases the overall efficiency because of the deviations from optimal generation spot.

Conventional power systems operate effectively without storage, but efficiency of the systems can be increased with the integration of ESSs. Additionally, ESSs can be used to reduce the effects of renewable generation integration and increase reliability and stability of the systems. An ESS can be described in terms of the following properties [10]:

**Storage capacity (kWh)** is the amount of energy that can be stored by the ESS.

**Power rating (kW)** is the rate of energy transfer per unit time which can be supplied or consumed by the ESS.

**Energy to power ratio** is the ratio of ESS storage capacity to its power rating. ESSs with higher energy to power ratio can deliver power for longer periods. ESS applications for different energy to power ratios are listed at Table 1 [10].

Table 1: ESS applications for different energy to power ratios [10]

| **Seconds to minutes** | **Daily** | **Weekly to monthly** |
|---|---|---|
| Primary/Secondary frequency control<br>Spinning reserve<br>Voltage control<br>Black start capability<br>Peak shaving<br>Island grids<br>Uninterruptible power supply | Tertiary frequency control<br>Standing reserve<br>Load leveling<br>Island grids<br>Residential storage systems<br>Uninterruptible power supply | Storage for “Dark calm” periods<br>Island grids |

**Energy density ($kWh/m^3$)** is the ratio of ESS storage capacity to its volume. ESSs with high energy density can be used for applications where the volume of storage system is limited.

**Power density ($kW/m^3$)** is the ratio of ESS power rating to its volume. ESSs with high power density can be used for high power applications with short duration of power usage.

**Specific energy (kWh/kg)** is the ratio of ESS storage capacity to its weight. ESSs with high specific energy can be used for application with high energy demand and weight limitations.

**Specific power (kW/kg)** is the ratio of ESS power rating to its weight. ESSs with high specific power can be used for applications with high power demand and weight limitations.

**Depth of discharge** is the ratio of discharged energy to storage capacity of the ESS. For a fully discharged storage system, depth of discharge (DoD) is 100%.

**State of charge** is the ratio of remaining energy to usable storage capacity of the ESS. For a fully charged storage system, state of charge (SoC) is 100%.

**Efficiency** is the ratio of output energy to input energy of ESS. With increasing losses, efficiency of the ESS decreases.

**Self discharge** is the energy loss of ESS due to internal processes at standby.

**Start-up time (sec)** is the time period between power request and first power delivery.

**Ramp-up time (sec)** is the time period required from zero to full power transition.

**Ramp rate (kW/sec)** is the ratio of maximum power to ramp-up time.

**Deployment/response time (sec)** is the time period between power request and full power delivery. In Fig. 6 [10], time parameters of an ESS can be observed.

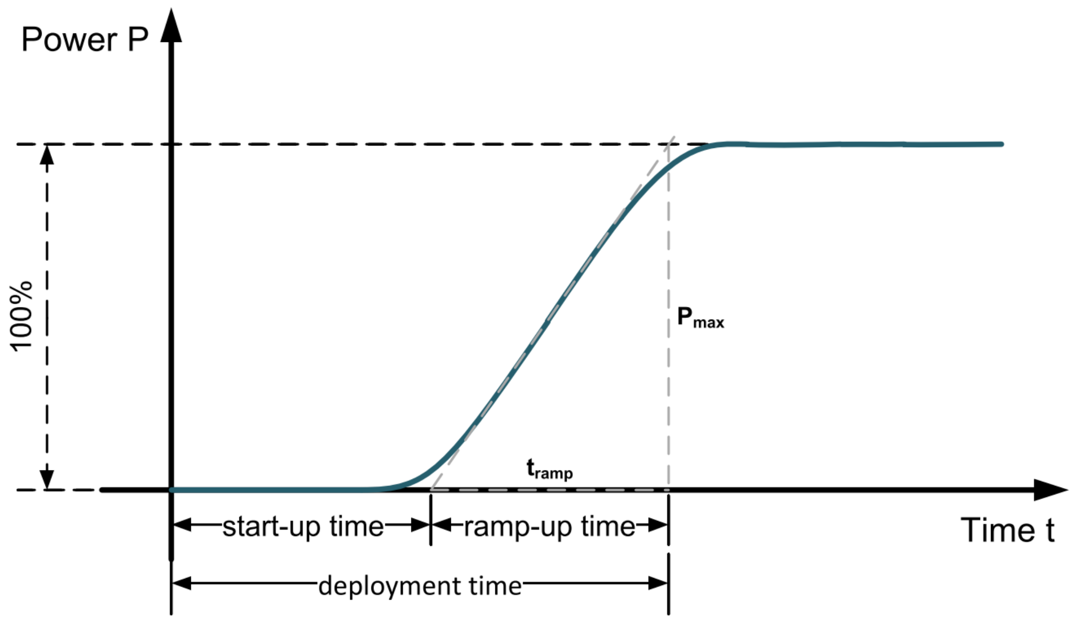


Fig. 6: Response time of an ESS [10]

**Full cycle** is the complete discharging and charging process of the ESS. Discharging the system to minimum energy limit and then charging it to maximum energy limit is regarded as one full cycle of the ESS.

**Equivalent full cycle** is the overall discharging and charging process with any DoD per cycle divided by available capacity. Discharge&charge of the system 2 times with 50% DoD or 4 times with 25% DoD are both considered as one equivalent full cycle.

**Cycle life** is the number of full cycles that can be delivered by the ESS under specified conditions before the ESS cannot meet specified criteria.

**Calendar life** is the lifetime of the ESS when it is not used.

### 2.2.1 Classification of Energy Storage Systems

A widely-used classification of energy storage technologies is according to the form of energy used; mechanical, electrochemical, chemical, electromagnetic and thermal, which is presented in Fig. 7 [5].

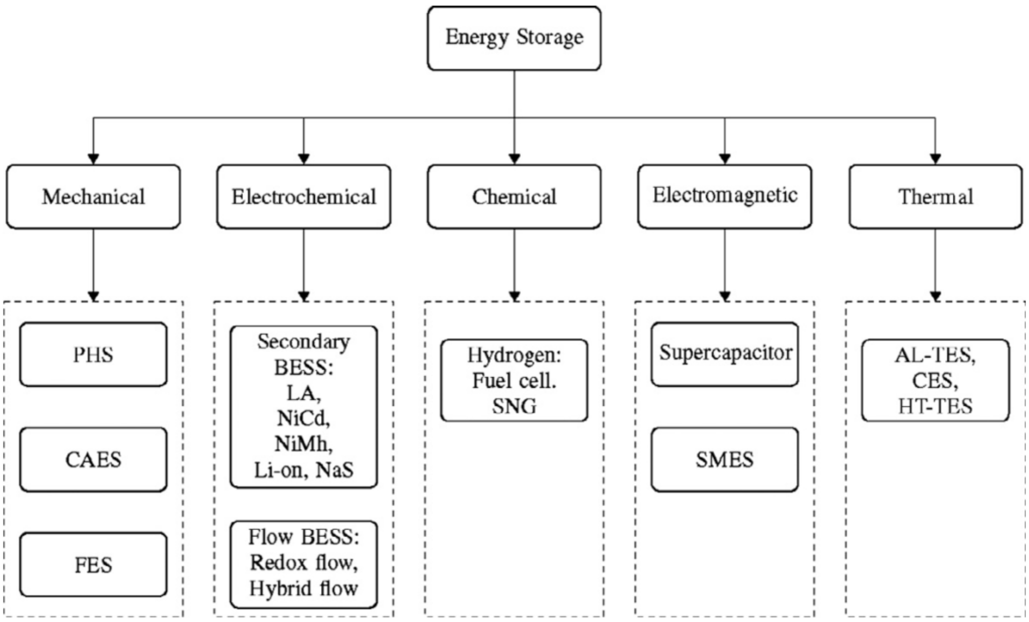


Fig. 7: Classification of energy storage technologies [5]

ESSs can be also categorized according to duration and frequency of the power supply [10]:

**Short-term ESSs:** Short term ESSs are used for instant energy supply. This type of ESSs are used mainly in primary and secondary frequency control and reactive power compensation applications. This storage systems have low energy to power ratio of minutes and high charging and discharging rates. Generally, equivalent full cycles per day are very high for these systems.

**Medium-term ESSs:** Medium-term ESSs are used for matching the demand fluctuations between day and night. Energy to power ratio of this systems are typically several hours. These type of systems have typically one or two equivalent full cycles per day.

**Long-term ESSs:** Long-term ESSs are used for power supply during several days or weeks. These systems have very high energy to power ratio, and due to this high energy capacity and relatively low power, the number of equivalent full cycles per year is very few. This kind of systems can be used to overcome “dark calm” periods, when power generation shortage occurs in power systems with high renewable energy penetration. Different energy storage technologies with their rated power and energy levels are shown in Fig. 8 [11].

ESS applications with their definitions for generation support, transmission and distribution support and end-customer uses are also listed at Table 2 [12].

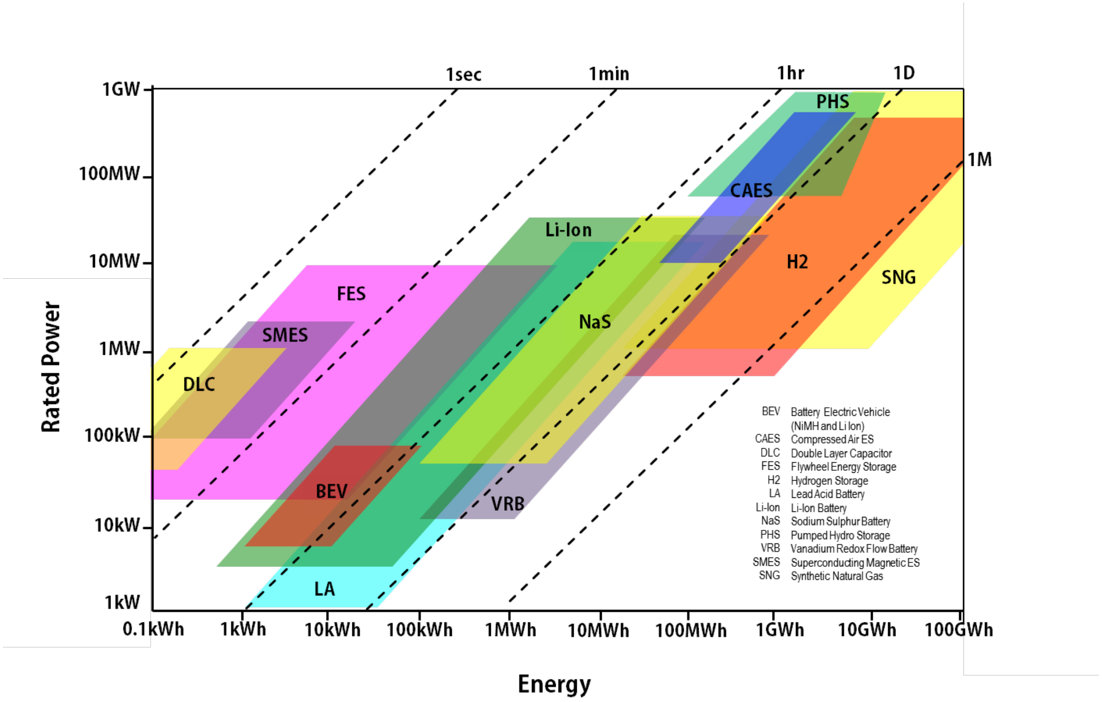


Fig. 8: Comparison of storage technologies [11]

Table 2: Generation and system-level applications of ESSs [12]

| Usage area | Application | Description |
|---|---|---|
| **Generation and system level applications** | **Wholesale Energy Services** | Utility-scale storage systems for bidding into energy, capacity and ancillary services markets |
| | **Renewable Integration** | Utility-scale storage systems providing renewable time shifting, load and ancillary services for grid integration |
| | **Stationary Storage for Transmission and Distribution Support** | Storage systems for improving transmission and distribution system utilization factor, and transmission and distribution capital deferral |
| **Transmission and distribution system applcations** | **Transportable Storage for Transmission and Distribution Support** | Transportable storage systems for transmission and distribution system support and transmission and distribution deferral at multiple sites as needed |
| | **Distributed Energy Storage Systems** | Centrally managed modular systems providing increased customer reliability, grid transmission and distribution support and potentially ancillary services |
| | **Energy Services Company Aggregated Systems** | Residential-customer-sited storage aggregated and centrally managed to provide distribution system benefits |
| | **Commercial and Industrial Power Quality and Reliability** | Systems to provide power quality and reliability to commercial and industrial customers |
| **End-user applications** | **Commercial and Industrial Energy Management** | Systems to reduce time of use energy charges and demand charges for commercial and industrial customers |
| | **Home Energy Management** | Systems to shift retail load to reduce time of use energy and demand changes |
| | **Home Backup** | Systems for backup power for home offices with high reliability value |

### 2.2.2 Applications of Energy Storage Systems

ESS applications for wind integration support can be categorized as generation-side, grid-side and demand-side applications [5]:

**Generation-side Applications:**

Unlike conventional power plants, wind farm power output cannot be controlled in a strict way as a result of intermittent nature of wind energy. Power intermittency, ramp rates and limiting wind power output are the main challenges coming along with wind power integration into the power systems [13]. Looking from the generation-side to overall system, controllability of a wind farm can be increased with the usage of ESSs.

**Time shifting:** Wind power generation is a non-dispatchable source of electricity production and can only be forecasted with a limited certainty. The mismatch between wind power output with the demand pattern, e.g. high wind power generation during off-peak demand periods and vise versa, is a big challenge as the difference between peak and off-peak periods of the system net-load increases. Energy storage technologies can be used to match the wind power generation with load cycles by storing extra energy during high wind power generation and releasing it later during peak demand periods. In time shifting applications, huge amount of energy is required to be stored for long time periods, so it is important to consider storage capacity and energy to power ratio parameters of the ESSs in these applications.

**Output smoothing:** Wind power generation can have sudden drops and steep rises as a result of variable wind speed. System stability will be affected with the sudden power output changes which will create frequency and voltage fluctuations. Power output of a wind farm can be smoothed out with energy storage technology applications, by storing excess energy during instantaneous increase in power generation and releasing the stored energy during sudden output power drops.

Ramping capability of the ESSs is the most important parameter in these applications, as the storage system must match the quick changes of wind power output.

**Transmission utilization efficiency:** Rich wind resources are often located in remote locations and transmission networks limitations becomes a serious problem to supply the energy demand, which is far from wind farm sites [14]. With the usage of energy storage technology, efficiency of transmission utilization can be increased by reducing congestion over the network. Additionally, transmission and distribution upgrades can be deferred or in some cases avoided at all with proper usage of the ESSs.

**Grid-side Applications:**

Increasing wind power generation reduces the stability and reliability of the grid, because of the intermittent nature of these supplies. Considering the distributed generation of wind farms over the system, net variability of the entire grid is lower compared to the integration of single wind power plant, so overall requirement of services is less than considering grid-side applications. Energy storage technologies can be used to provide ancillary services to decrease the impact of wind power generation over system stability and reliability.

**Energy arbitrage/load leveling:** In the electricity market, electricity prices vary during peak and off-peak hours. The variation of market clearing prices in Turkey in 2016 can be observed in Fig. 9 [15]. Energy storage technologies can be used to reduce the gap between peak and off-peak prices, by storing low-cost energy during off-peak periods and releasing stored energy during peak periods with the higher price [16].


Fig. 9: Average of hourly market clearing prices in Turkey (2016) [15]

**Frequency regulation:** ESSs can be used to provide frequency regulation to the wind farms by controlling active power output of storage with frequency deviation. Primary frequency control can be applied by using droop control in local systems. Active power output of the ESSs can be controlled according to frequency change on the grid [17]. For secondary frequency control, an automatic control system can arrange the power outputs to response frequency deviations.

**Inertia emulation:** The impact of sudden wind generation changes on frequency changes can be reduced by increasing inertia of grid. Apparent inertia of a grid can be increased with the integration of the ESSs, by controlling the active power output of the storage systems.

**Oscillation damping:** Sudden power changes of wind farms can cause oscillations in an interconnected system which may led to synchronization loss of some machines [18]. Energy storage technologies can be used to damp the system oscillations caused by variable wind generation output and increase the stability of the power system.

**Voltage control support:** Voltage stability of the grid can decrease with the variable nature of wind generation output. Integration of energy storage technologies can increase reactive power support for voltage regulation by controlling converters connected to the grid [18].

**Low Voltage Ride Through support:** Today, low voltage ride through (LVRT) capability of wind turbine generators are determined by grid codes. During severe grid faults, wind turbines should remain connected for reactive power support and in some situations maximum reactive power needs to be delivered by wind turbines [19]. For such cases, energy storage technologies can support the power need by converters and control systems.

**Reserve application:** For the stability and reliability of the system, emergency reserves are required as a result of forecast error of wind power output. Integration of energy storage technologies can be an option for the reserve applications.

**Emergency power supply:** In the situation of a fatal failure, ESSs can be used to energize the power system from a shut-down condition [20].

**Transmission utilization efficiency:** Integration of energy storage technologies into power systems can increase the efficiency of transmission network usage and transmission and distribution costs can be reduced by deferral of network upgrade.

**Demand-side Applications:**

With the combination of ESSs and DSM, ancillary services can be provided for the grid using huge amount of variable loads as a virtual power plant (VPP).

### 2.2.3 Planning of Energy Storage Systems

Technical characteristics of an ESS, such as storage capacity, rating power and charging/discharging duration range can be determined by analyzing characteristics of a wind farm.

Fluctuations of wind generation output at different time scales is an important parameter for the ESS selection. While generation reserve and energy dispatch applications are related to low frequency fluctuations (minutes to hours), power system frequency control applications are related to high frequency applications (seconds to minutes) [21]. High frequency fluctuations on the wind power output has an insignificant overall effect [22] and can be damped out by inertia of the turbine generator [23]. As a result, it is required that energy to power ratio of the ESSs to be in the order of a few hours for wind integration support [5].

As the increasing rating capacity of wind farms is considered, large-scale energy storage technologies are required for wind integration applications. BESS, PHS and CAES technologies are suitable for the large-scale applications for their capability of storing energy for long periods at a high power rating. Among these three technologies, BESS is more suitable for the purpose, as PHS and CAES are limited by topographical constraints [5]. By taking account of these findings and rapid development in battery technology and cost reduction, it is decided to study the BESS technology for the wind power applications. Battery types are introduced in the following with their advantages and disadvantages [24]:

**Lead-acid Batteries:**

**Advantages:** Easy installation, high efficiency, low investment cost, long storage duration due to low self-discharge.

**Disadvantages:** Poor performance at low and ambient temperatures, short life time, periodic maintenance requirements, low specific power, difficulties in frequent power cycling, environmentally unfriendly.

**Nickel-based Batteries:**

**Advantages:** Fast discharge cycles due to low internal resistance, long life time, low maintenance requirements, good low temperature performance, wide range of size and performance options, lowest cost per cycle [25], integration with renewable energy sources for long term storage [26].

**Disadvantages:** Higher cost compared to lead-acid batteries even they have lower energy efficiency and higher discharge rate [27, 28], high toxicity, full charge deficiency after series of full discharges [22], continuous maintenance requirements.

**Sodium-Sulphur Batteries:**

**Advantages:** Long life time, high power density, high energy capacity, good performance at ambient conditions [27].

**Disadvantages:** Thermal management, safety.

**Lithium-based Batteries:**

Lithium-based Batteries can be divided into two categories; Lithium-Ion Batteries and Lithium-Polymer Batteries.

**Advantages:** High energy density and specific energy, fast charge and discharge capability, high efficiency, light weight, decreasing cost [25].

**Disadvantages:** Life time dependency on operating temperature, necessity to maintain a safe operating voltage and temperature due to high flammablity and fragility, maximum charge and discharge current limitations.

**Flow Batteries:**

Flow Batteries can be divided into three categories; Vanadium Redox Flow Batteries (VRB), Zinc-Bromine Flow Batteries (ZBB) and Polysulphide-Bromide Flow Batteries (PSB).

**Advantages:** Scalability, high power, long duration, fast response and quick transition between charge and discharge modes, zero self-discharge [28].

**Disadvantages:** High operating cost, low energy density, thermal management need for safety.

Two mainly used battery types; lithium-ion, lead-acid batteries and their characteristics are tabulated including future expectations at Table 3 and Table 4 [10],

Table 3 Characteristics of lithium-ion batteries [10]

| Lithium-ion batteries | | |
|---|---|---|
| **Parameters** | **2013** | **2030 (Expected)** |
| **Round-trip efficiency** | 83-86 % | 85-92 % |
| **Energy density** | 200-350 Wh/l | 250-550 Wh/l |
| **Power density** | 100-3500 W/l | 100-5000 W/l |
| **Cycle life** | 1000-5000 full cycles | 3000-10000 full cycles |
| **Calender life** | 5-20 years (depending on temperature and SoC) | 10-30 years (depending on temperature and SoC) |
| **Depth of discharge** | Up to 100 % | Up to 100 % |
| **Self discharge** | 5 % per month | 1 % per month |
| **Power installation cost (converter)** | 150-200 €/kW | 35-65 €/kW |
| **Energy installation cost** | 300-800 €/kW | 150-300 €/kW |
| **Deployment time** | 3-5 ms | |
| **Site requirements** | None | |
| **Main applications** | Frequency control<br>Voltage control<br>Peak shaving<br>Load leveling<br>Electromobility<br>Residential storage systems | |

Table 4 Characteristics of lead-acid batteries [10]

| Lead-acid batteries | | |
|---|---|---|
| **Parameters** | **2013** | **2030 (Expected)** |
| **Round-trip efficiency** | 75-80 % | 78-85 % |
| **Energy density** | 50-100 Wh/l | 50-130 Wh/l |
| **Power density** | 10-500 W/l | 10-1000 W/l |
| **Cycle life** | 500-2000 full cycles | 1500-5000 full cycles |
| **Calendar life** | 5-15 years (depending on temperature and SoC) | 10-20 years (depending on temperature and SoC) |
| **Depth of discharge** | 70 % | 80 % |
| **Self discharge** | 0.1-0.4 % per day | 0.05-0.2 % per day |
| **Power installation cost (converter)** | 150-200 €/kW | 35-65 €/kW |
| **Energy installation cost** | 100-250 €/kW | 50-80 €/kW |
| **Deployment time** | 3-5 ms | |
| **Site requirements** | Ventilation due to gassing | |
| **Main applications** | Frequency control<br>Peak shaving<br>Load leveling<br>Island grids<br>Residential storage systems<br>Uninterruptible power supply | |

## 2.3 Demand-side Management

In a conventional power system, the balance between generation and demand is maintained by controlling the power output of limited number of power plants. However, with the increasing penetration of renewable generation to the system, dispatch of generation capacity to provide the required services to follow the load profile becoming much more challenging. As an alternative way, controlling load-side to increase flexibility of the power system attracts increasing attention. Loads can be dispatched according to system needs with the help of global communication infrastructure and embedded systems [29].

Flexible loads can be scheduled considering the grid needs with demand-side management (DSM). If individual loads can be aggregated and controlled on command according to the requirement of power systems, the result will be the same as generation dispatch. For example, turning off a large number of loads when the demand exceeds generation will have the same effect of increasing generation or vice versa.

### 2.3.1 Classification of Demand Side Management

DSM technologies can be categorized according to timing and impact of the applications on customer process, which can be observed in Fig. 10 [29].

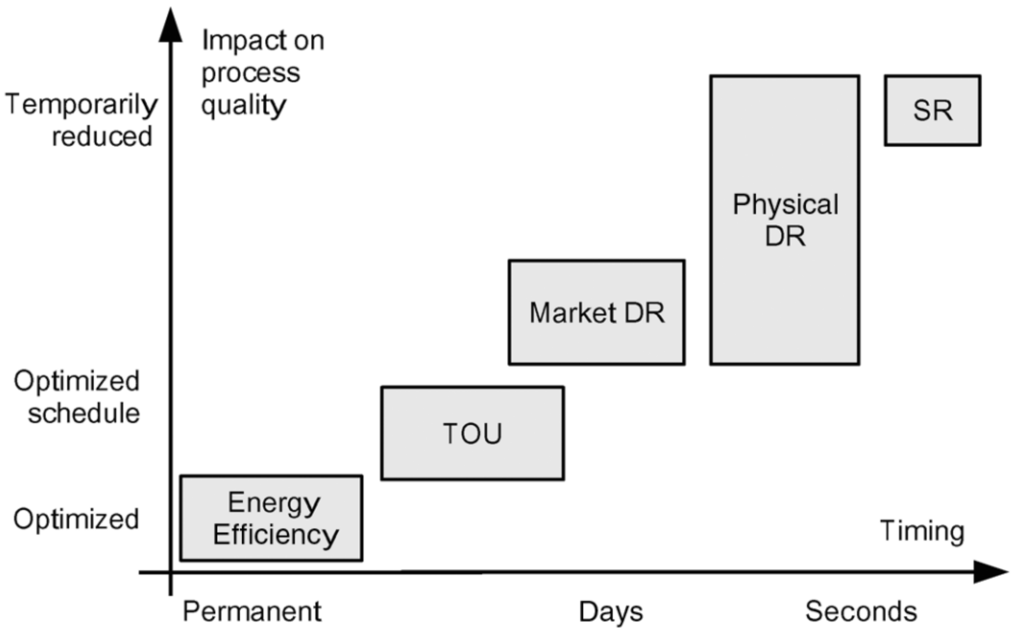


Fig. 10: DSM categories according to timing and impact of the appliances [29]

**Energy Efficiency (EE):** EE applications include increasing the efficiency of appliances and improvements on the system properties. Changing a refrigerator with a more efficient one or applying thermal insulation to a building are some examples that can be considered as EE applications. In addition, behavioral changes of users to increase efficiency of energy usage can be included in these applications.

**Time of Use (ToU):** In ToU tariffs, electricity prices change according to power consumption at that time. Electricity prices for third quarter of 2017 in Turkey for different end-users are tabulated at Table 5 [30]. Considering the high difference between electricity prices for different time periods of the day, customers are encouraged to arrange their power consumption to reduce the overall cost.

Table 5: Electric prices for different time periods in Turkey [30]

| **End-user** | **Day period (06:00-17:00)** | **Peak period (17:00-22:00)** | **Night period (22:00-06:00)** |
|---|---|---|---|
| **Industrial** | 28.94 kr/kW | 44.85 kr/kW | 17.46 kr/kW |
| **Commercial** | 33.34 kr/kW | 50.27 kr/kW | 21.10 kr/kW |
| **Residential** | 33.05 kr/kW | 49.98 kr/kW | 20.81 kr/kW |

**Demand Response (DR):** DR is defined as controlling flexible loads to shift power consumption from peak periods to off-peak periods. By doing so, energy consumption is not decreased but only shifted through time. However, by shifting peak power consumption through time, the overall efficiency of power system is increased. Difference impacts of EE and DR applications can be observed in Fig. 11 [29]. While EE applications affect the energy consumption permanently, DR applications only delay the energy consumption.

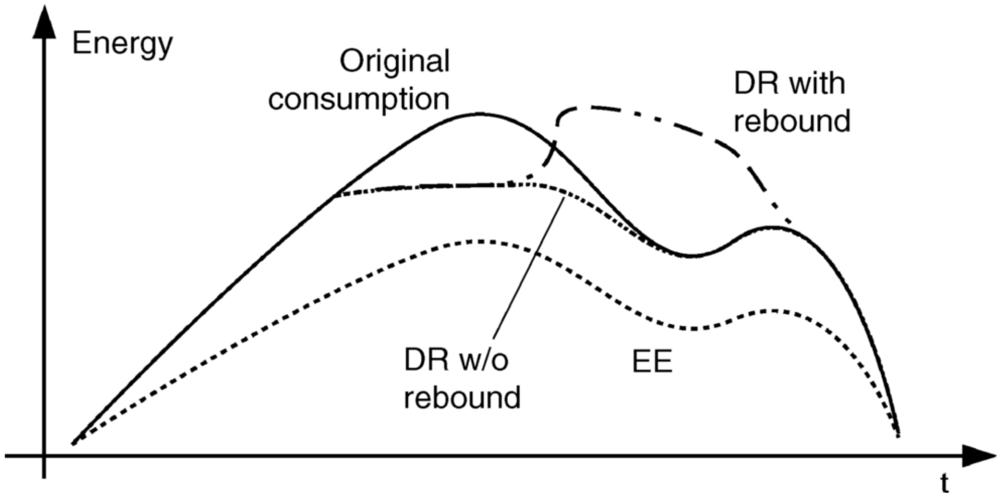


Fig. 11: Impact of energy efficiency and demand response [29]

**Spinning Reserve (SR):** Combination of large number of loads can be used for frequency regulation applications, namely primary and secondary frequency control. Primary frequency control is done by controlling active power, considering frequency changes over time. In secondary frequency control, frequency is restored with additional active power to the system. With SR applications, combination of large number of loads can be controlled like a virtual power plant with negative power output to the grid.

### 2.3.2 Applications of Demand Side Management

DSM applications can be classified according to the time scale of the load control (from milliseconds to hours) [31]:

**Under a second:** Frequency changes in a system can be observed and dispatchable loads can respond to these changes to maintain system security. Either loads can be shut down when a steep frequency drop occurs on the grid, or they can response to frequency changes according to frequency error, similar like droop control of conventional power plants. As wind power plants can participate to frequency control only in small amounts, demand dispatch can be a solution for the intermittent wind power output.

**Seconds to minutes:** The ancillary services for power system regulation is provided by power plants in today's power systems. An alternative way for serving these services to the power system is DSM. By controlling high number of loads with fast response, regulation can be provided in an efficient way.

**Hours:** Dispatchable loads can be controlled to match highly varying wind generation profile for a wind farm or even for a region, depending on the limits of aggregated loads. Rapid changes in wind power generation can be followed by DSM control, as the flexible loads generally have a fast response time. With the introduction of DSM into the power systems, the required fast-response generation capacity will be reduced.

### 2.3.3 Planning of Demand Side Management

DSM takes advantage of controllable loads and support the grid considering changing needs, so in order to dispatch loads, some flexibility is needed in demand-side. Some suitable loads for DSM applications can be listed as follows [31]:

- Dishwashers
- Washers and dryers
- Electric hot water heaters
- Heating, ventilation and air-conditioning (HVAC) systems
- Battery charges for consumer electronics
- Plug-in vehicles

Considering the large number of aggregated flexible loads, demand dispatch can be an important factor for the power systems applications. However, there are some constraints for the flexible loads, so important parameters must be defined for each individual load, such as minimum and maximum power limits, how much and when energy is needed and number of cycles for a given time period. The main objective of demand dispatch is to serve the grid needs by dispatching loads while considering these limitations. Suitable services for the power systems can be developed by considering power and energy limitations of flexible loads as well as their response characteristics.

HVAC systems are chosen to be controlled in this study, as they are responsible for a high percentage of energy usage in residential and commercial. End-use energy consumption in United States for residential and commercial sectors in 2016 with the expectations in 2040 can be observed in Fig. 12 [32]. Considering the energy consumption share overall, HVAC systems can participate in matching generation and load, as well as ancillary services to support grid with suitable control methods.

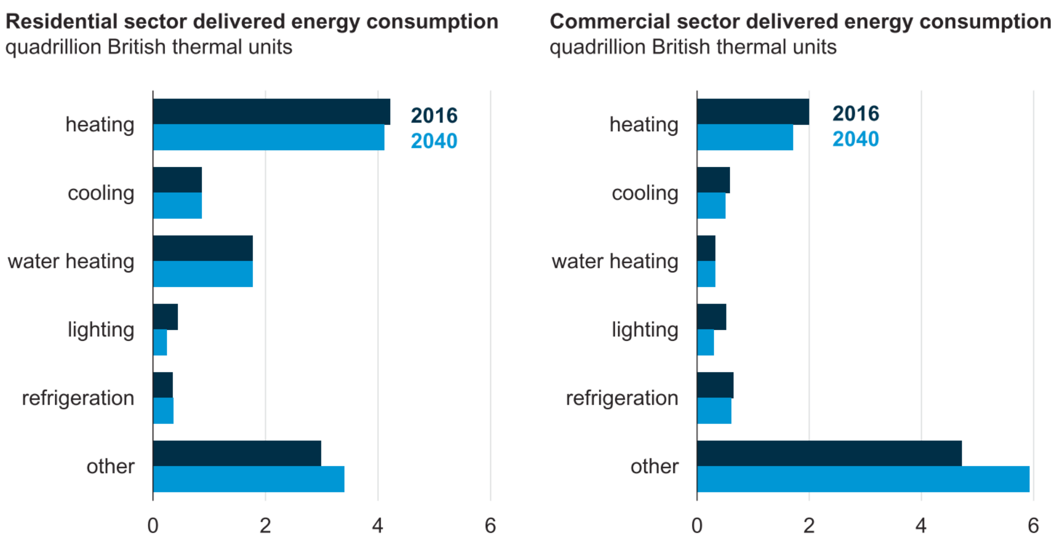


Fig. 12: End-use energy consumption for residential and commercial sectors [32]

Thermal behavior of a HVAC unit without an external control can observed in Fig. 13 [33]. In this case, HVAC unit works as a heater only and operates according to set temperature limits with the help of the thermostat, simply turning on when room temperature is under the lower set limit and turning off when room temperature is over the upper set limit.

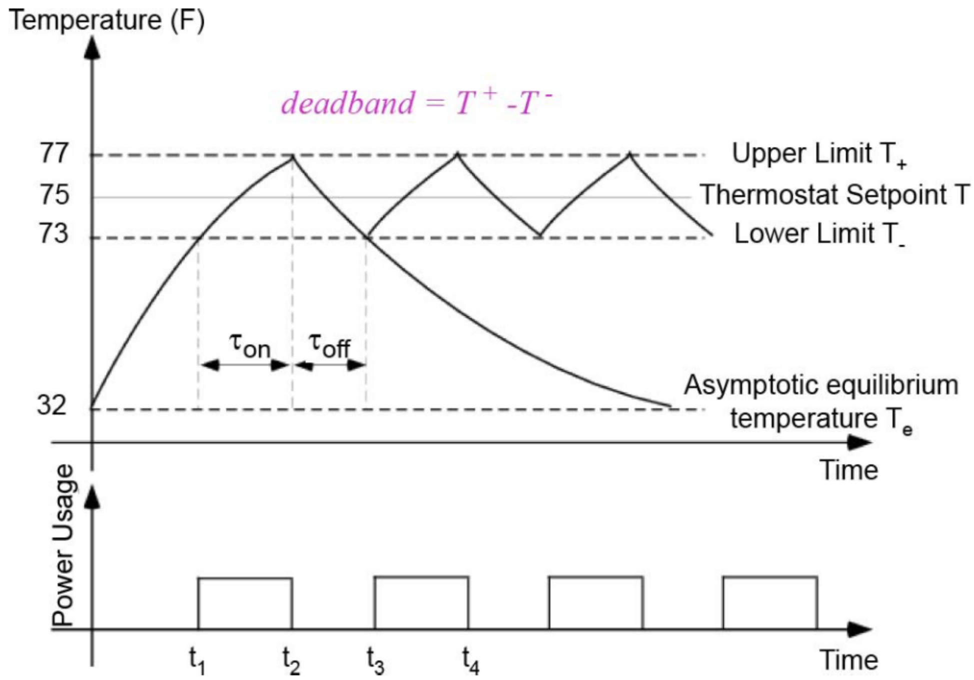


Fig. 13: Thermal behavior of a HVAC unit [33]

The thermal output of a HVAC unit can be described using **energy efficiency ratio** (EER), which is the ratio of output cooling power to electrical input power and **coefficient of performance** (CoP), which is the ratio of output heating power to electrical input power of the HVAC unit.

DSM applications can have different control methods, which usually divided into two categorizes; direct load control (DLC) and indirect load control (ILC) [34], [35]. A detailed categorization according to control methods is presented in Fig. 14 [36]:

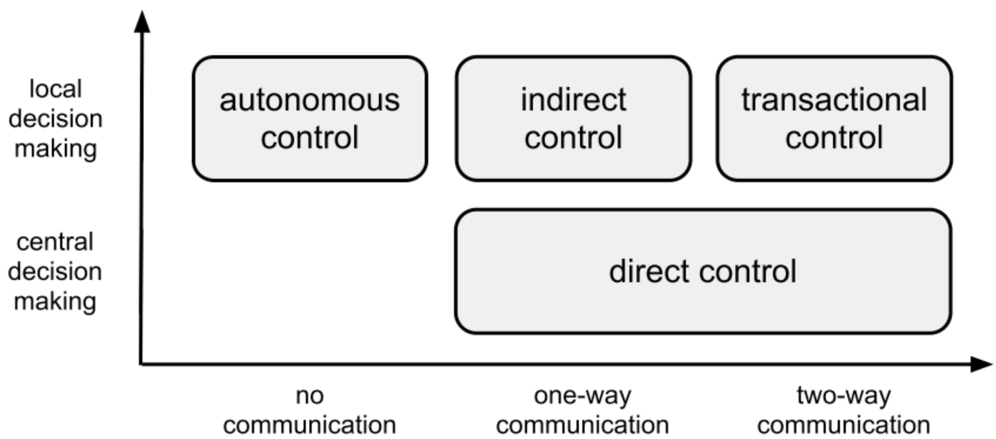


Fig. 14: DSM categories according to control methods [36]

**Direct control:**

In direct control method, specific commands are sent to controllable loads via an external controller, which has the information about load operation. One-way or two-way communication can be used for information exchange between direct controller and loads. For one-way communication infrastructure, commands are sent to loads via external controller and it is expected from the loads to follow the specific commands if there isn't any violation of operation limits or failure. In case of two-way communication structure, the loads acknowledge the specific commands sent by external controller and send back the information about the applicability of the command with the status.

Different types of direct load control schemes commonly found in literature are deferred consumption, delta control, scheduled operation and direct control [37];

**Deferred consumption:** The consumption of the certain amount of energy is shifted through time. The command signal sent to load is a time shift ($\Delta t$).

**Delta control:** The consumption of the certain amount of energy is decreased or increased, which may result in change of operation duration. The command signal sent to load is a power difference ($\Delta P$).

**Scheduled operation:** Schedule of power set points with time stamps is sent to load and executed locally. The command signal includes power set point and time stamp (P, t).

**Direct control:** Power set point is sent to load in real-time. The command signal is power set point (P).

Operations of different direct load control types are presented in Fig. 15 by illustrating before and after power consumption with corresponding control methods [36].

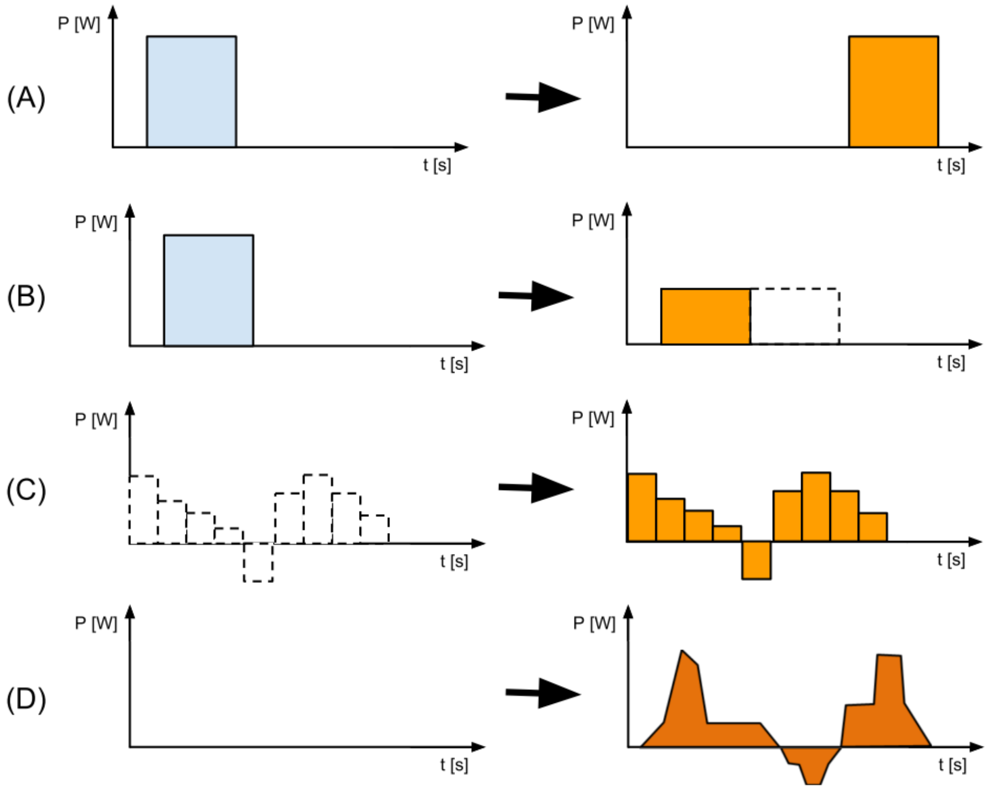


Fig. 15: DSM direct load control operations: (A) Deferred consumption, (B) Delta control, (C) Scheduled operation, (D) Direct control [36]

**Indirect Control:**

In case of indirect control, loads receive the command signals sent by an external controller, but not necessarily behave as commanded. Two main characteristics of indirect load control are indirectness of the relationship between control objective and observables, which can lead random unobservable behavior and non-deterministic behavior of the loads due to independent decision making of the local controllers [35]. As the communication is one-way, external controller does not receive any feedback from the loads. External controller broadcasts command signals in indirect control method and any load can behave according to commands at any time or loads can follow special and dynamic objectives depending on local decision making algorithms. Indirect control methods can be divided into two categories; control with indirect functional variables indirect control via price signals [36].

**Control with indirect functional variables:** External controller objective is to modify the operation of the loads by sending a command signal to the load which contains a functional variable. As the state of the loads are unknown due to the lack of feedback, system behavior is non-deterministic. Functional variable signal can be generated by using the observable or estimated aggregated response and statistical models can be used to decrease the mismatch between control goal and system behavior.

**Indirect control via price signals:** External controller uses energy prices to generate command signals. Instantaneous and scheduled price operations are two options for this control type. In case of instantaneous price operation, the command signal consists of a single price with a time stamp which states the validation time of the price. In case of scheduled price operation, command signal consists a time series of prices and time stamps for the future.

**<u>Transactional control:</u>**

Transactional control method depends on negotiations in a bid-based market in which loads are used for trading products, e.g. power, energy and flexibility. Local controllers independently determine the bidding amount and compete with each other. With the transactions, local controllers optimize the consumption by using equilibrium value determined by the market. This control method includes the price negotiation and biding strategies. Local controllers decide the bid offers and operation of the loads. Price equilibrium for all participating loads are determined by the constructed market.

**Autonomous control:**

Local measurements are used to control the loads locally in autonomous control method. Communication infrastructure is not needed as all the decisions are taken by local controllers and due to independent local measurements, loads can response faster compared to the other control methods. This control method can be used for local power system services.

## 2.4 Summary and Conclusion

This chapter started with the introduction of power system flexibility concept and two proposed methods for additional flexibility on power systems are presented; energy storage system (ESS) technologies and demand-side management (DSM) with their characteristics, classifications and applications.

Suitable ESSs are compared in order to choose the most suitable technology for the integration to wind energy generation. Due to their capability of storing energy for long periods at a high power rating, BESS, PHS and CAES are the most suitable technologies for the wind generation integration purposes. However, considering the limitation of PHS and CAES due to topographical constraints, BESS is chosen for the energy storage technology to be used in this study. By looking the advantages and disadvantages of commercial battery types, lithium-ion battery is found more suitable due to high energy and power density, fast charge and discharge capability, long life time and high efficiency.

HVAC units are chosen for the demand-side management application as they occupy a high percentage of energy usage in residential and commercial areas. Aggregated HVAC units in fact can be used for grid support in different applications. In order to control HVAC units according to changing grid power for every time step, direct control method is chosen in this study and all HVAC units are controlled by a central controller.

# CHAPTER 3

# TRANSMISSION AND DISTRIBUTION UPGRADE DEFERRAL

## 3.1 Introduction

As a result of continuous growing peak demand, overloading of the existing transmission and distribution (T&D) structures used in the power systems over time becomes a critical problem. In order to maintain the safety of the system and the equipment, upgrade of the present structures becomes inevitable even in the situation of modest overload. The main problem of upgrading an existing T&D structure is the high investment cost, which is highly variable due to various factors such as; installation requirements and location. However, upgrade of a T&D system can be deferred in specific conditions, depending on the characteristics of the power flow. Viability of T&D upgrade deferral can be examined by checking some criteria over present systems [38]:

- High T&D investment cost (direct costs and "soft" costs such as; utility reputation and customer goodwill)
- High peak-to-average demand ratio (peak demand for short periods)
- Modest projected overload (expected peak overloading on the T&D structure by a modest amount)
- Slow peak demand growth
- Uncertainty about timing and/or likelihood of block load additions
- T&D construction delays or construction resource constraints
- Budget optimization (T&D upgrade competing with other important projects for capital)

- Benefit aggregation (additional benefits provided by the distributed resource)
  - on-peak energy
  - electric supply capacity
  - value enhancement for electricity from renewable energy resources
  - reduced transmission congestion and energy losses
  - electricity end-user energy/demand bill reduction
  - electric supply reserve capacity
  - improved local power quality and/or reliability

In need of an upgrade over existing structure, T&D upgrade factor is defined as the ratio of load carrying capacity to be added to present T&D structure. An example of the T&D upgrade deferral concept is demonstrated in Fig. 16 [38].

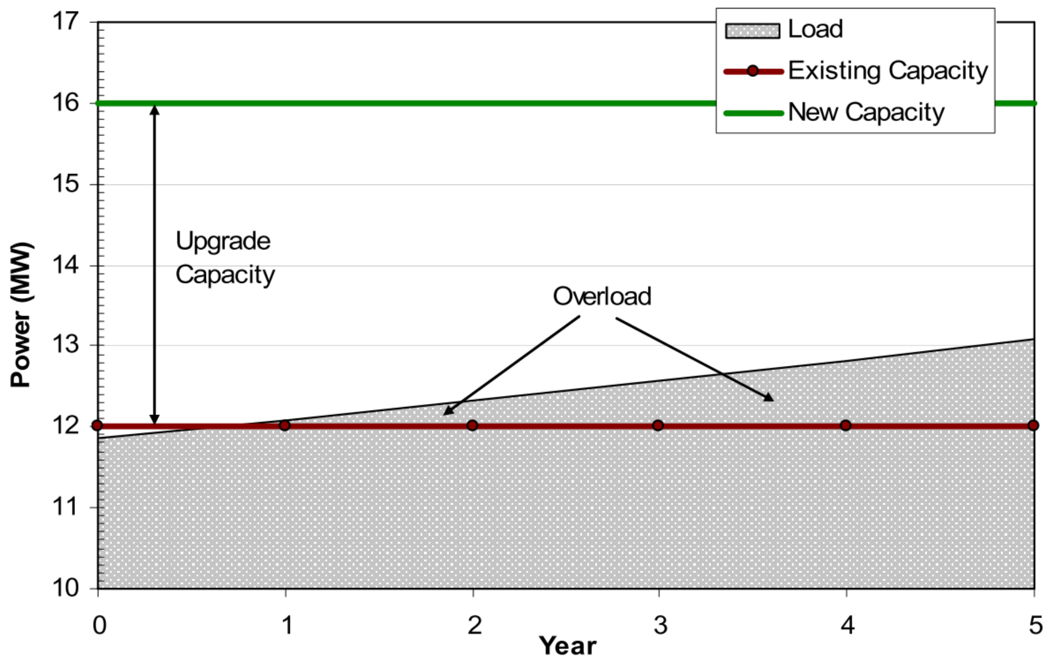


Fig. 16: Planned upgrade of a distribution system due to increasing peak demand [38]

For the illustrated case in Fig. 16, an existing distribution system with a rated load carrying capacity of 12 MW is expected to be overloaded next year, considering a 2% load growth rate per year. In order to avert overloading of the equipment, load carrying capacity of the distribution structure is planned to be increased with an upgrade factor of 0.33, from 12 MW to 16 MW. Taking the modest overload projection over the structure into account, required upgrade can be delayed for some time using proper solutions.

Energy storage systems (ESSs) and demand-side management (DSM) can be used to deliver a portion of peak demand and large T&D structure upgrades can be deferred with small capacity additions. ESS usage for the transmission system upgrade deferral is illustrated in Fig. 17 [39]. In this example, storage system is committed to absorbing excess power flow on the transmission line only. As it can be observed from the figure, BESS is discharged when the power demand exceeds the threshold level in order to compensate the excess power over the transmission line and charged shortly after, when the power demand drops below the critical level.

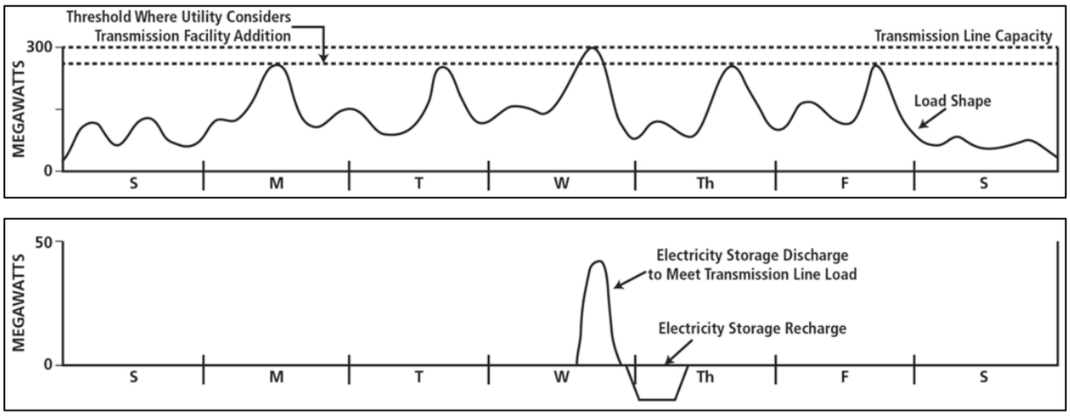


Fig. 17: ESS usage for transmission system upgrade deferral [39]

In this chapter, constructed scenario for the T&D upgrade deferral application is explained with the analysis of obtained data integrated into the scenario. Modeling and approaches of ESS and DSM are also introduced in the next part of this chapter.

### 3.2 Description of the Scenario

In this study, a hypothetical scenario is constructed where a wind farm connected to a near organized industrial zone and the overall system is connected to the grid as shown in Fig. 18. Capacity of grid-side transmission structure is occupied by the power flow from/to the grid ($P_{grid}$) depending on the wind power generation ($P_{wind}$) and industrial power consumption ($P_{oiz}$). Overload on the grid-side is examined for the different cases; increase on the industrial load through years and block capacity addition to the wind farm. Impact of ESS and DSM integration on the grid-side structure is analyzed for these cases.

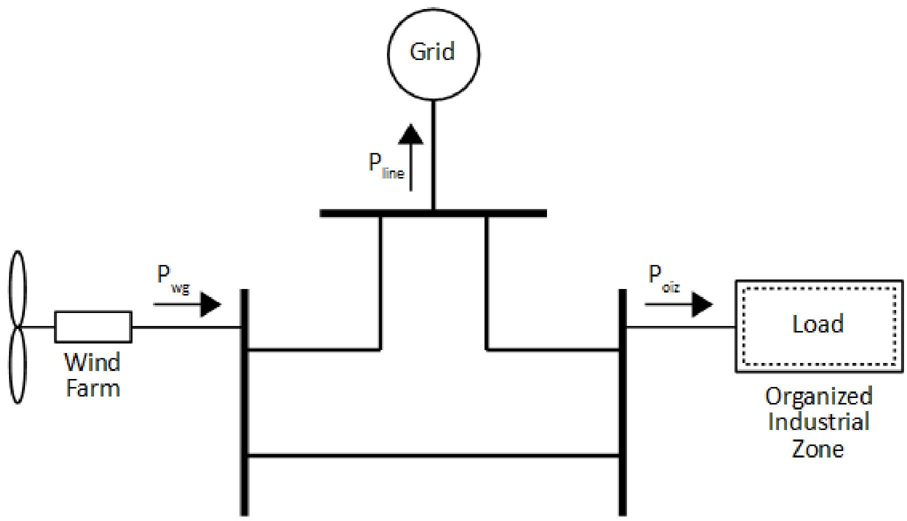


Fig. 18: Drawing of the constructed system

Wind power generation and organized industrial zone power consumption data used in this study are obtained from Monitoring and Forecasting System Development for Wind Generated Electrical Power in Turkey (RİTM, in native initials) and National Power Quality Project (MGKP, in native initials) of The Scientific and Technological Research Council of Turkey, Marmara Research Center, Energy Institute (TÜBİTAK MAM EE, in native initials). In order to use the available data, raw data are organized and processed using R [40], which is an open source software environment for data manipulation, calculation and graphical display.

Missing data are common problem for data analysis and can have significant effect considering the overall study. Percentage and distribution of missing data are two important factors which needed to be taken account. Databases of aforementioned projects are examined in order to find suitable data to be used in this study.

With the analysis of these databases, wind generation measurements of a wind farm in the Aegean Region of Turkey and industrial consumption measurements of an organized industrial zone in the Marmara Region of Turkey is decided to be used for this study. Both generation and consumption data are acquired in 2016 with 10 minute intervals. Summary of missing values in raw data used in this study is tabulated at Table 6. The percentage of missing data is 0.77% for wind power generation, which is an acceptable value considering the distribution of missing values. Industrial power consumption data used in this study does not contain any missing value. The missing data are interpolated by Kalman Smoothing method using the “imputeTS” package of R [41].

Table 6: Information of missing values in chosen data

| | **Wind power generation** | **Industrial power consumption** |
|---|---|---|
| **Missing data percentage** | %0.77 | - |
| **Maximum number of consecutive missing data** | 8 | - |

Summary of wind power generation and industrial power consumption data after imputation of missing values are provided at Table 7. The high difference between installed wind generation and industrial consumption is not favourable for this study, as the generation and consumption wanted to be close to each other for the constructed scenario to limit both power supplied to and drawn from the grid between same levels. In order to compensate for the difference, wind power generation data is multiplied by 4, which brings the maximum generation and consumption levels near 160 MW.

Table 7: Summary of data after imputation of missing values

| **Data** | **Min. (MW)** | **1st Qu. (MW)** | **Median (MW)** | **Mean (MW)** | **3rd Qu. (MW)** | **Max. (MW)** |
|---|---|---|---|---|---|---|
| **Wind generation** | -0.24 | 2.78 | 9.62 | 13.2 | 22.13 | 40.83 |
| **Industrial consumption** | -0.39 | 95.73 | 115.45 | 104.72 | 126.09 | 157.03 |

Power generation of the wind farm used in this study is plotted in Fig. 19. Highly variable nature of wind generation through the year can be seen in this figure. Daily wind generation of the wind farm is also plotted in Fig. 20, where the steep rises and sudden drops of the power output can be observed in more detail. An important factor for the feasibility of transmission-side upgrade deferral is the high peak to average ratio of power flow, which is the case for power generation of the wind farm. Low percentage of high power generation levels can be observed from the histogram presented in Fig. 21.

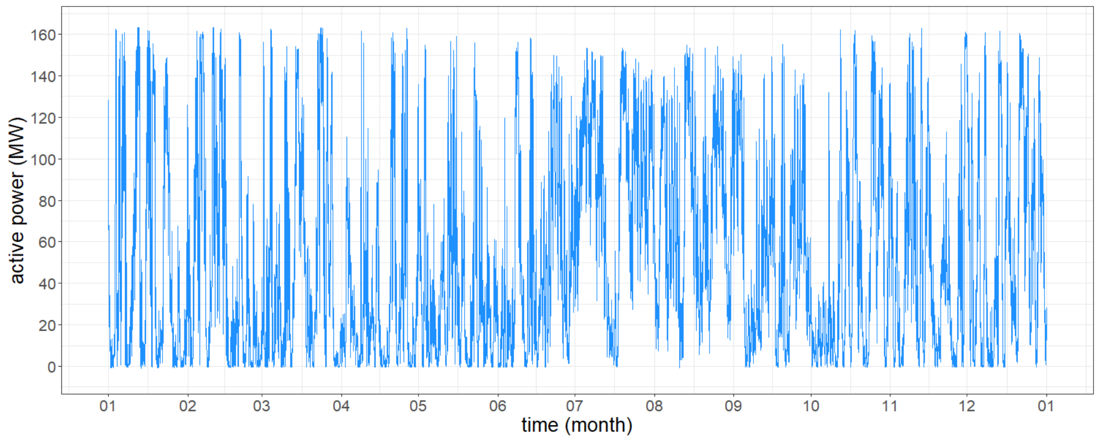


Fig. 19: Power generation of the wind farm throughout the year

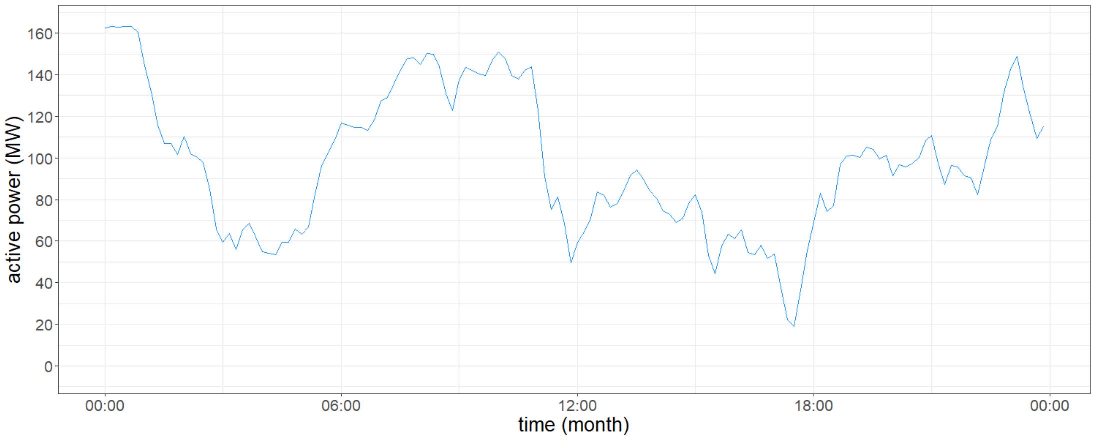


Fig. 20: Daily power generation of the wind farm

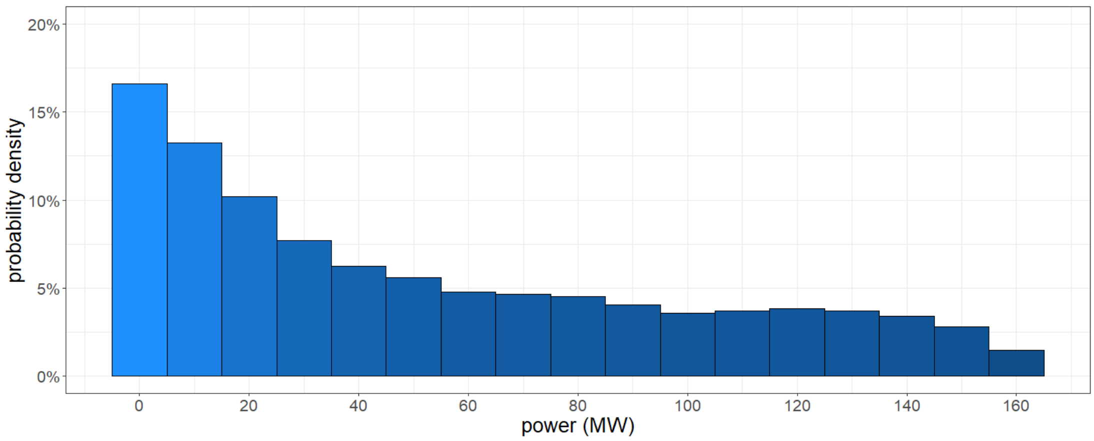


Fig. 21: Histogram of the wind power generation

Power consumption of the organized industrial zone used in this study is plotted in Fig. 22. Weekly pattern of the industrial power consumption can be observed throughout the year except the first week of July and second week of September, which are corresponding to holidays in Turkey, Ramadan and Sacrifice Feasts, respectively. Weekly power consumption of the industrial zone starting from Monday is also plotted in Fig. 23. As it can be observed from this figure, power consumption on weekdays has a similar pattern and on weekends, power consumption decreases significantly compared to weekdays. Power consumption levels are distributed around 120 MW for weekdays and 50 MW for weekends, which can be observed from the histogram presented in Fig. 24.

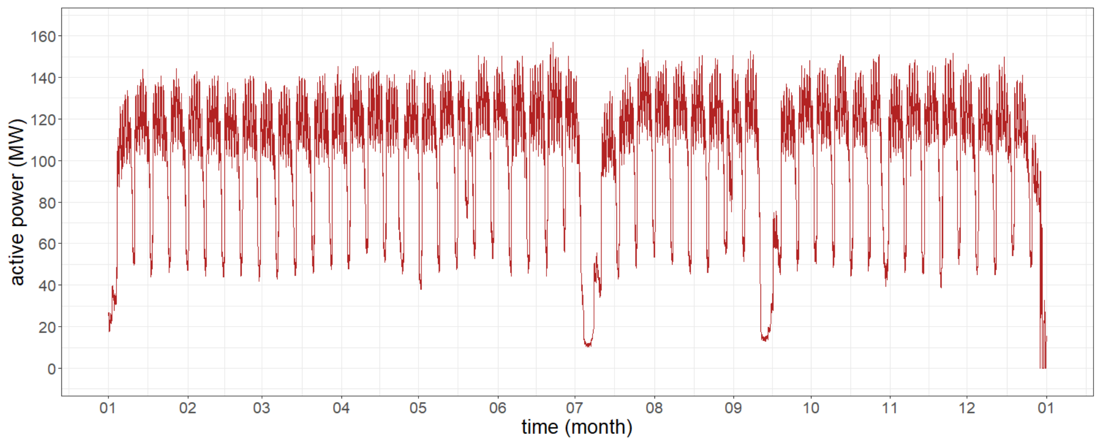


Fig. 22: Power consumption of the organized industrial zone throughout the year

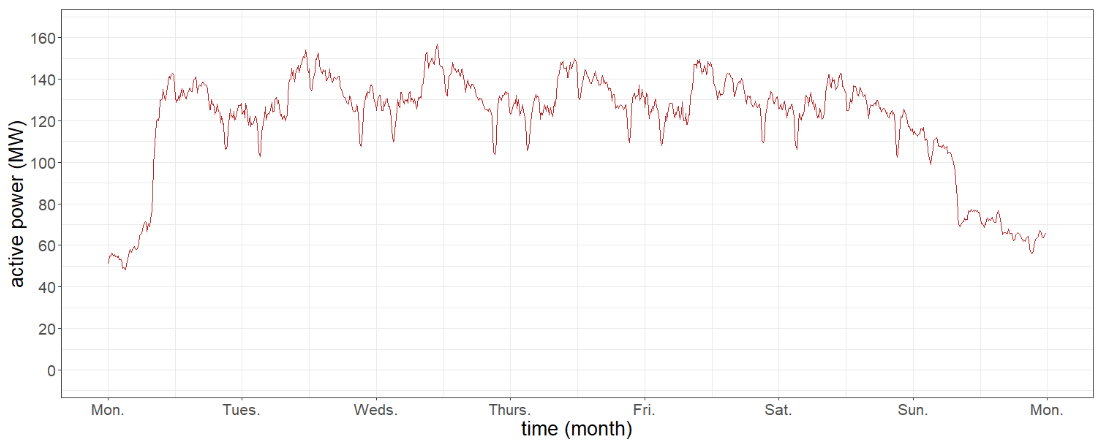


Fig. 23: Weekly power consumption of the organized industrial zone

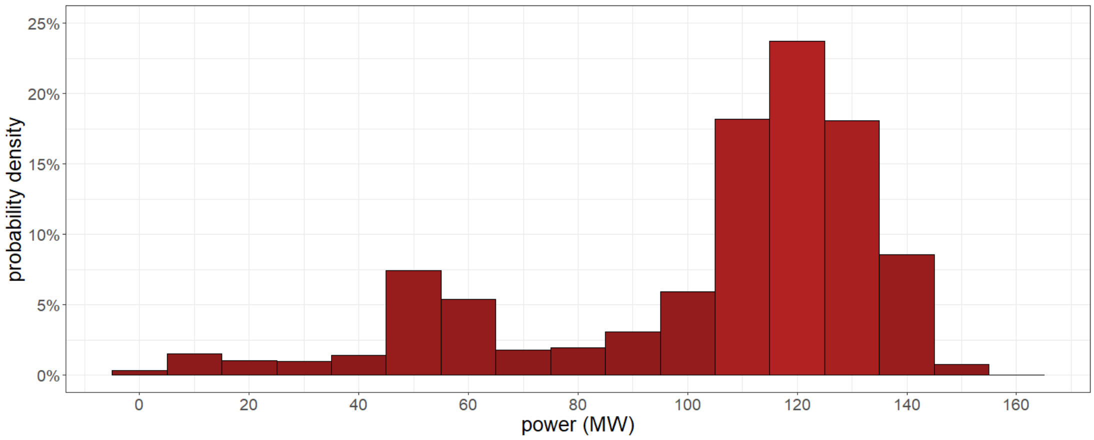


Fig. 24: Histogram of the organized industrial zone power consumption

With the integration of aforementioned wind generation and industrial consumption profiles to the system, power flow on the transmission-side and histogram of power flow levels are shown in Fig. 25 and Fig. 26, respectively. In these figures, positive power values correspond to excess power generation of wind farm which is supplied to the grid, and negative power values correspond to power demand from the grid where wind generation cannot supply the industrial load. Low percentage of peak power flow can be observed in these figures. Summary of the power flow data is also tabulated at Table 8.

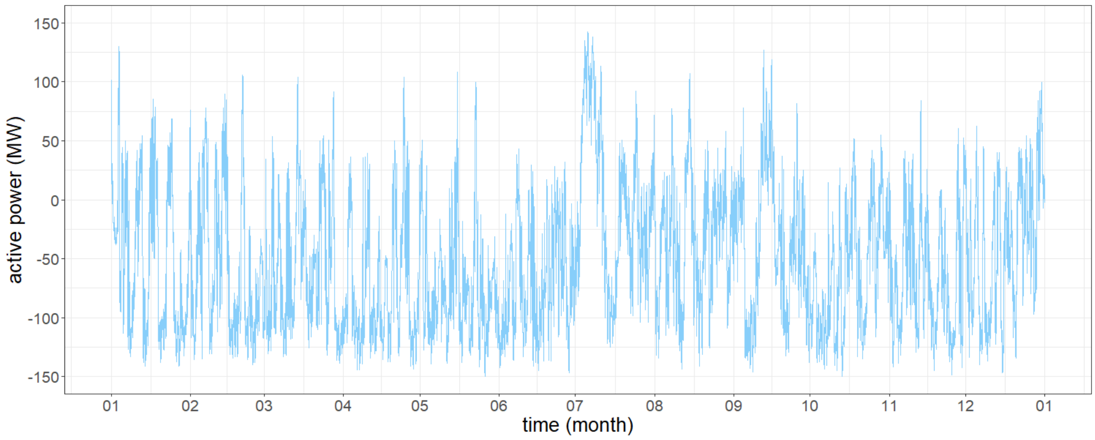


Fig. 25: Power flow on transmission-side as a result of chosen generation and load profiles

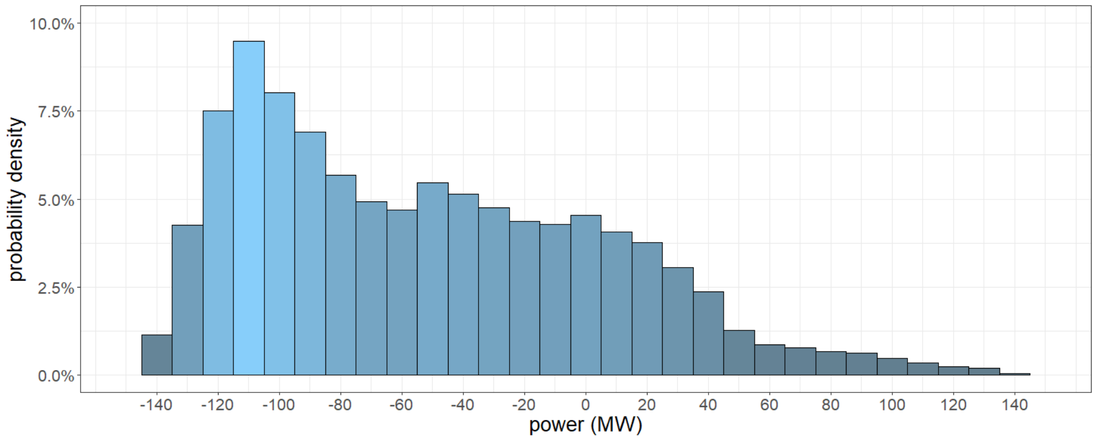


Fig. 26: Histogram of power flow on transmission-side

Table 8: Summary of power flow from/to grid

| Data | Min. (MW) | $1^{st}$ Qu. (MW) | Median (MW) | Mean (MW) | $3^{rd}$ Qu. (MW) | Max. (MW) |
|---|---|---|---|---|---|---|
| **Grid power flow** | -149.77 | -102.13 | -60.46 | -51.94 | -8.98 | 142.40 |

Int this study, the impact of ESS and DSM on transmission-side upgrade deferral is investigated for the explained scenario. As mentioned in the previous chapter, battery energy storage system (BESS) is chosen for the energy storage technology on the system. The BESS is integrated to the system at the point of common coupling of wind farm as shown in Fig. 27. For DSM application, HVAC units are determined as a suitable option because of the high percentage of end-use consumption occupied by these units. HVAC units' power load over the system is considered in the consumption of organized industrial zone. The main purpose of this study is to use ESS and DSM concepts, in our case BESS and aggregated HVAC units, as a tool to absorb the excess power flow occurring on the transmission-side of the system.

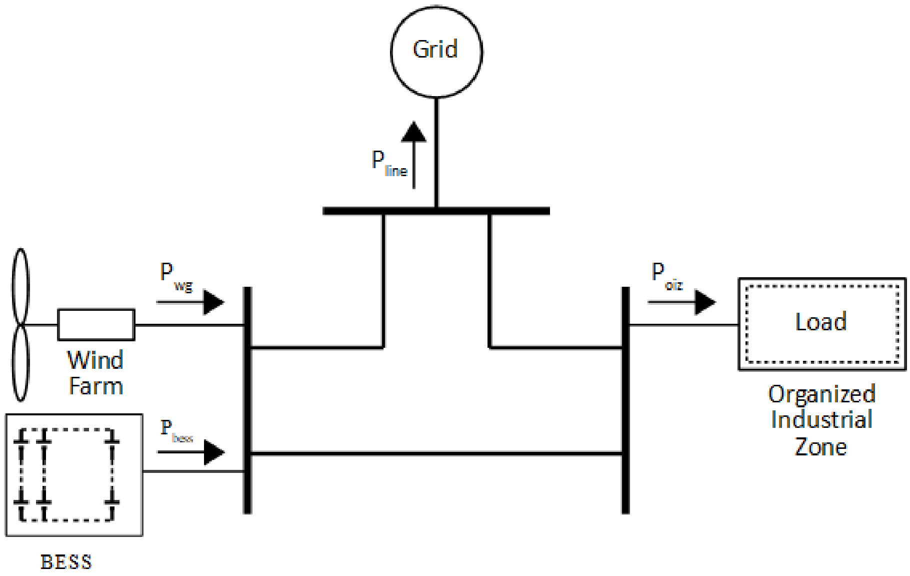


Fig. 27: Drawing of the system with BESS integration

### 3.3 Modeling and Approaches

#### 3.3.1 Power Flow on Grid Side

Analysis of transmission upgrade deferral by keeping power flow on transmission-side within the limits of existing structures is the main purpose of this study. Power flow constraints of the transmission-side is expressed as follows:

$$-P_{grid}^{max} \leq P_{wg}^{k} + P_{bess}^{k} - P_{oiz}^{k} \leq P_{grid}^{max} \tag{3.1}$$

where:

| | |
|---|---|
| $P_{grid}^{max}$ | maximum transmission line loading capacity (MW) |
| $P_{wg}^{k}$ | wind farm power generation at time step k (MW) |
| $P_{oiz}^{k}$ | organized industrial zone power consumption at time step k (MW) |

$P_{bess}^{k}$ BESS power output at time step k (MW)

### 3.3.2 Battery Energy Storage System

BESS can operate in three different modes; discharging, charging and idle. In charging mode, batteries are charged with the power drawn from grid and BESS can be considered as a load. In discharging mode, the power is supplied to the grid with discharge of the batteries and BESS can be considered as a generation unit. In idle mode, batteries are neither charged nor discharged. Mode variables of BESS are tabulated at Table 9.

Table 9: Mode variables of BESS

| Variable | Idle mode | Discharging mode | Charging mode |
|---|---|---|---|
| $u_{dsch}^{k}$ | 0 | 1 | 0 |
| $u_{ch}^{k}$ | 0 | 0 | 1 |

$$u_{dsch}^{k} + u_{ch}^{k} \leq 1 \tag{3.2}$$

where:

$u_{dsch}^{k}$ discharging mode indicator of the BESS at time step k

$u_{ch}^{k}$ charging mode indicator of the BESS at time step k

Discharging efficiency of a BESS is defined as the ratio of power supplied to grid to rate of change in stored energy in BESS. Charging efficiency of a BESS is defined as the ratio of rate of change in stored energy in BESS to power drawn from grid. Battery charging and discharging powers are limited by the physical and chemical characteristics of the BESS. Considering these information, power equations of the BESS are expressed as follows:

$$u_{ch}^{k} P_{bess,rt} \frac{1}{n_{ch}} \leq P_{bess}^{k} \leq u_{dsch}^{k} P_{bess,rt} n_{dsch} \tag{3.3}$$

where:

| | |
|---|---|
| $P_{bess,rt}$ | rated power of the BESS (MW) |
| $P_{bess}^{k}$ | power output of the BESS at time step k (MW) |
| $u_{dsch}^{k}$ | discharging mode indicator of the BESS at time step k |
| $u_{ch}^{k}$ | charging mode indicator of the BESS at time step k |
| $\eta_{dsch}$ | discharging efficiency of the BESS |
| $\eta_{ch}$ | charging efficiency of the BESS |

SoC of a battery is defined as available capacity of the battery expressed as a percentage of its rated capacity. SoC is an indication of how longer a battery can continue to perform before recharging is needed [42]. Depleting or overcharging a battery is not desired, so proper limitations (i.e., 30%-100%) should be defined for SoC of the battery. Considering these information, SoC equations of the BESS are expressed as follows:

$$SoC^{k+1} = SoC^{k} \frac{-\left(u_{dsch} \frac{1}{\eta_{dsch}} + u_{ch} \eta_{ch}\right) P_{bess}^{k} \frac{\Delta t}{60}}{S_{cap}} \tag{3.4}$$

$$SoC^{min} \leq SoC^{k} \leq SoC^{max} \tag{3.5}$$

where:

| | |
|---|---|
| $SoC^{k}$ | state of charge of BESS at time step k |

| | |
|---|---|
| $P_{bess}^{k}$ | power output of the BESS at time step k (MW) |
| $u_{dsch}^{k}$ | discharging mode indicator of the BESS at time step k |
| $u_{ch}^{k}$ | charging mode indicator of the BESS at time step k |
| $\eta_{dsch}$ | discharging efficiency of the BESS |
| $\eta_{ch}$ | charging efficiency of the BESS |
| $S_{cap}$ | storage capacity of the BESS (MWh) |
| $P_{bess,rt}$ | rated power of the BESS (MW) |
| $SoC^{min}$ | minimum allowed state of charge of the BESS |
| $SoC^{max}$ | maximum allowed state of charge of the BESS |
| $\Delta t$ | time interval between time steps (minutes) |

### 3.3.3 Heating, Ventilation and Air Conditioning Units

HVAC units can operate in three different modes; cooling, heating and idle. In cooling mode, HVAC units draw power from the grid to extract heat from the room. In heating mode, HVAC units draw power from the grid to release heat to the room. In idle mode, HVAC units neither cool nor heat the room. Mode variables of HVAC units are tabulated at Table 10.

Table 10: Mode variables of HVAC unit

| **Variable** | **Idle mode** | **Heating mode** | **Cooling mode** |
|---|---|---|---|
| $(u_{ht})_i^k$ | 0 | 1 | 0 |
| $(u_{cl})_i^k$ | 0 | 0 | 1 |

$$(u_{ht})_i^k + (u_{cl})_i^k \leq 1 \tag{3.6}$$

where:

| | |
|---|---|
| $(u_{ht})_i^k$ | heating mode indicator of the $HVAC_i$ at time step k |
| $(u_{cl})_i^k$ | cooling mode indicator of the $HVAC_i$ at time step k |

HVAC units draw power from the grid both for cooling and heating modes. Total power drawn from the grid by HVACs can be expressed as follows:

$$P_{hvac}^k = \sum_{i=1}^{N} [(P_{hvac,rt})_i ((u_{ht})_i^k + (u_{cl})_i^k)] \tag{3.7}$$

where:

| | |
|---|---|
| $P_{hvac}^k$ | power demand of aggregated HVAC units at time step k (MW) |
| $(P_{hvac,rt})_i$ | rated power of $HVAC_i$ (MW) |
| $(u_{ht})_i^k$ | heating mode indicator of the $HVAC_i$ at time step k |
| $(u_{cl})_i^k$ | cooling mode indicator of the $HVAC_i$ at time step k |
| $N$ | number of HVAC units |

Coefficient of performance (COP) is defined as the as the ratio of the delivered heat to electrical input power and energy efficiency ratio (EER) is defined as the ratio of the removed heat to electrical input power [43]. Considering these information, thermal power output of HVAC units can be expressed as follows:

$$(Q_{hvac})_i^k = (P_{hvac,rt})_i (((u_{ht})_i^k COP_i) - ((u_{cl})_i^k EER_i)) \tag{3.8}$$

where:

| | |
|---|---|
| $(Q_{hvac})_i^k$ | equivalent thermal power output of $HVAC_i$ at time step k (MW) |
| $(P_{hvac,rt})_i$ | rated power of $HVAC_i$ (MW) |

| | |
|---|---|
| $(u_{ht})_i^k$ | heating mode indicator of the $HVAC_i$ at time step k |
| $(u_{cl})_i^k$ | cooling mode indicator of the $HVAC_i$ at time step k |
| $COP_i$ | coefficient of performance of $HVAC_i$ |
| $EER_i$ | energy efficiency ratio of $HVAC_i$ |

For modeling the HVAC units, a simplified model for temperature dynamics of a space can be created using a resistance-capacitance (RC) circuit analogy [33], [44]. The simplified thermal mass model can be used for energy conversion problems, considering entire building and average temperature of all building spaces, as shown in Fig. 28. The representation of temperature dynamics in discrete time is stated in Eq. 3.7. The building temperature variation is controlled within a temperature band by HVAC units.

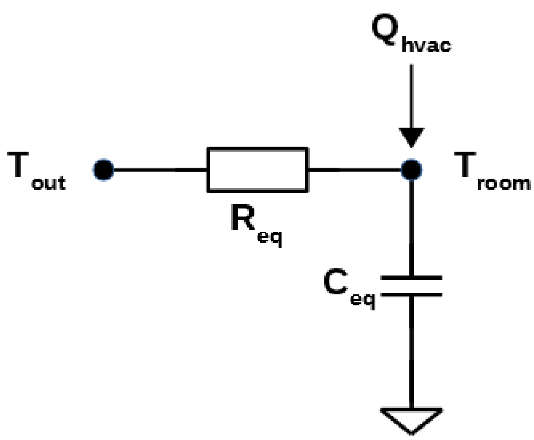


Fig. 28: Equivalent thermal parameters model of a space temperature [33], [44]

With the information given above, temperature equations of the buildings can be expressed as follows:

$$(T_{room})_i^{k+1} = (T_{room})_i^k + \left(\frac{(T_{out})_i^k - (T_{room})_i^k}{(R_{eq})_i (C_{eq})_i} + \frac{(Q_{hvac})_i^k}{(C_{eq})_i}\right)\Delta t \qquad (3.9)$$

$$(T_{room})_i^{min} < (T_{room})_i^k < (T_{room})_i^{max} \qquad (3.10)$$

where:

| | |
|---|---|
| $(T_{room})_i^k$ | temperature of building$_i$ at time step k (C$^o$) |
| $(T_{room})_i^{min}$ | minimum allowed temperature of building$_i$ (C$^o$) |
| $(T_{room})_i^{max}$ | maximum allowed temperature of building$_i$ (C$^o$) |
| $(T_{out})_i^k$ | temperature of ambient$_i$ at time step k (C$^o$) |
| $(R_{eq})_i$ | equivalent thermal resistance of building$_i$ (C$^o$/kW) |
| $(C_{eq})_i$ | equivalent thermal capacity of building$_i$ (kJ/C$^o$) |
| $(Q_{hvac})_i^k$ | equivalent thermal power output of HVAC$_i$ at time step k (kW) |

For this thesis, ambient temperature data is collected from U.S. Climate Reference Network (USCRN) [45], as there is no accessible weather datasets of Turkey for subhourly periods. In order to simulate suitable ambient temperature conditions for the operations of HVAC units, USCRN monthly temperature data for 2016 are compared with the monthly temperature data collected from Turkish State Meteorological Service (MGM, in native initials) [46] for an area in Turkish Aegean Region between 1929-2016. Monthly data of average temperature with minimum and maximum temperature averages taken from USCRN and MGM are tabulated at Table 11 and Table 12, and collected data are plotted in Fig. 29 and Fig. 30, respectively.

Table 11: Summary of monthly temperature data taken from USCRN [45]

| | Average Temperature (°C) | Average Low Temperature (°C) | Average High Temperature (°C) |
|---|---|---|---|
| **January** | 6.4 | 3.2 | 10.2 |
| **February** | 10.5 | 4.7 | 17.9 |
| **March** | 10.9 | 5.7 | 16.8 |
| **April** | 14.9 | 8.1 | 22.5 |
| **May** | 17.7 | 10.8 | 25.5 |
| **June** | 23.5 | 15.2 | 32.4 |
| **July** | 26.2 | 16.6 | 36.1 |
| **August** | 26.2 | 16.6 | 37.1 |
| **September** | 22.6 | 13.8 | 32.6 |
| **October** | 14.1 | 9.3 | 19.9 |
| **November** | 9.6 | 5.7 | 15.4 |
| **December** | 5.2 | 0.6 | 11.2 |

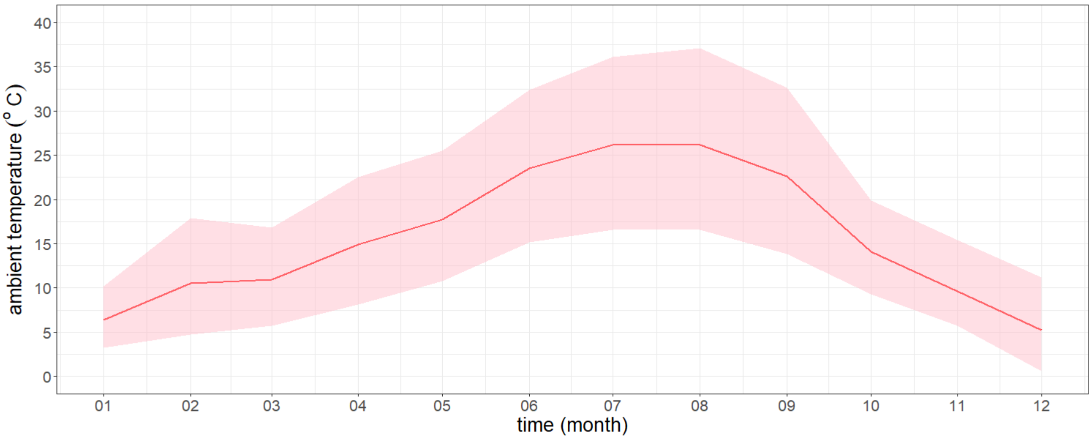


Fig. 29: Temperature of the chosen area from USCRN for one year period

Table 12: Summary of monthly temperature data taken from TSMS [46]

| | **Average Temperature (ºC)** | **Average Low Temperature (ºC)** | **Average High Temperature (ºC)** |
|---|---|---|---|
| **January** | 6.7 | 3.0 | 10.8 |
| **February** | 7.9 | 3.6 | 12.6 |
| **March** | 10.6 | 5.2 | 16.1 |
| **April** | 15.2 | 8.8 | 21.3 |
| **May** | 20.4 | 13.2 | 27 |
| **June** | 25.3 | 17.4 | 32.1 |
| **July** | 28.0 | 20.3 | 34.9 |
| **August** | 27.6 | 20.2 | 34.9 |
| **September** | 23.3 | 16.0 | 30.6 |
| **October** | 17.8 | 11.6 | 24.3 |
| **November** | 12.2 | 7.4 | 17.5 |
| **December** | 8.2 | 4.5 | 12.5 |

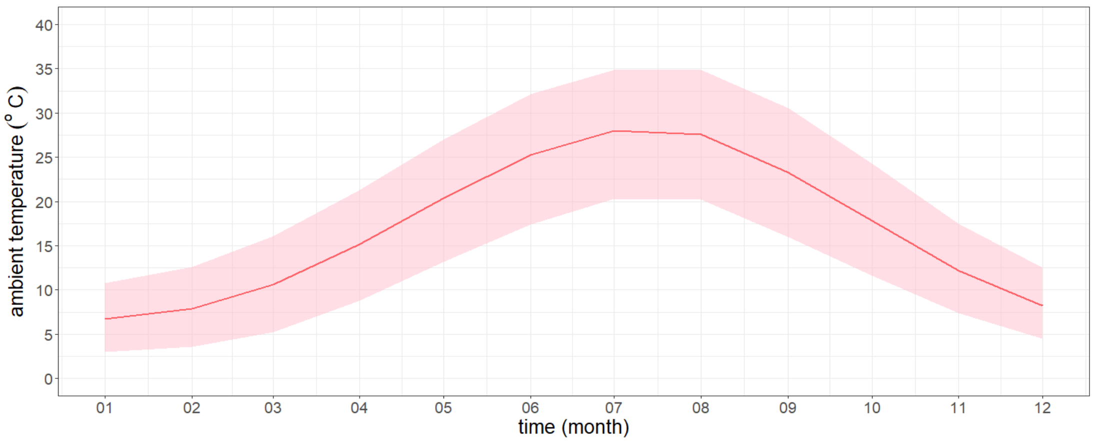


Fig. 30: Temperature of the chosen area from TSMS for one year period

### 3.4 Summary and Conclusion

This chapter starts with the explanation of T&D upgrade deferral application and the scenario constructed for this application is presented; a wind farm connected to a near organized zone and the overall system is connected to the grid.

Raw data of wind farm generation and industrial zone consumption used in this study are taken from a large databases of the RİTM and MGKP projects of TUBITAK MAM EE. Considering the suitable power levels, raw data are processed and processed data are investigated for a better understanding of the scenario.

At the end of this chapter, models used for the simulations are presented with equations and limit conditions. Mode variables of the BESS model are defined as idle, discharging and charging modes and output power and state of charge (SoC) equations and limitations of BESS model are generated using these mode variables. Mode variables of the HVAC model are defined as idle, heating and cooling modes and equations and limitations of the aggregated load power and thermal output power are generated using these mode variables. In order to model the thermal characteristics of a room, equivalent thermal parameters model (RC circuit analogy) is used. Room temperature equation is constructed using the thermal power output of the HVAC units and ambient temperature. Ambient temperature data is taken from U.S. Climate Reference Network (USCRN) [45], because of inaccessible weather datasets of Turkey for subhourly periods.

# CHAPTER 4

# SIMULATIONS AND RESULTS

## 4.1 Introduction

In this chapter, demand-side management (DSM) and energy storage system (ESS) control methods will be performed for the constructed scenario and corresponding results will be presented. Power flow on the transmission structure is analyzed using the active power component of the wind farm generation and industrial consumption data which are mentioned in the previous chapter. For the aforementioned scenario, maximum power supplied to the grid is 142 MW and maximum power drawn from the grid is 150 MW.

In order to define a power carrying capacity for the grid-side transmission structures in this scenario, conductor types used in Turkish electricity grid are examined and tabulated at Table 13 and Table 14 with their characteristics at 80 ºC conductor temperature, 40 ºC ambient temperature and 0.25 m/sec wind speed. Considering the maximum power flow on the grid-side transmission structure (both from and to the grid) of present scenario, it is reasonable to choose the grid-side structure as 154 kV, 795 MCM with 182 MVA capacity limit. It is important to note that, reactive power is not examined in this study and active power is implied by the introduced power values.

Table 13: 154 kV transmission line conductor types and characteristics

| Type | Total conductor area ($mm^2$) | Wire gauge (MCM) | Current carrying capacity (A) | Thermal capacity (MVA) |
|---|---|---|---|---|
| Hawk | 281 | 477 | 496 | 132 |
| Drake | 468.4 | 795 | 683 | 182 |
| Cardinal | 547 | 954 | 765 | 204 |
| 2B, Cardinal | 2x547 | 2x954 | 2x765 | 408 |
| Pheasant | 726 | 1272 | 925 | 247 |

Table 14: 380 kV transmission line conductor types and characteristics

| Type | Total conductor area ($mm^2$) | Wire gauge (MCM) | Current carrying capacity (A) | Thermal capacity (MVA) |
|---|---|---|---|---|
| 2B, Rail | 2x517 | 2x954 | 2x755 | 995 |
| 2B, Cardinal | 2x547 | 2x954 | 2x765 | 1005 |
| 3B, Cardinal | 3x547 | 3x954 | 3x765 | 1510 |
| 3B, Pheasant | 3x726 | 3x1272 | 3x925 | 1825 |

It is verified from Turkish Electricity Transmission Company (TEİAŞ, in native initials) that in case of a projected overload on an existing transmission structure, instead of an upgrade over the existing structure, a new parallel transmission line is assigned for the region. With this information, upgrade factor of the transmission-side is defined as 1, which corresponds to a new transmission structure with the same capacity (154 kV, 795 MCM transmission structure with another 182 MVA capacity, for this study). The information about the general capital expenses for a new transmission structure is also verified from TEİAŞ and tabulated at Table 15. As the expenses are highly variable for every project, depending mainly on the geography of the construction site, stated expenses can be considered as an average and used for a general understanding of the results.

Table 15: Approximate costs of transmission line equipments

| **Transmission line** | **Capital Expenditure (per MVA)** |
|---|---|
| Transmission line (per km) | 200 € |
| Power transformer | 4400 € |
| Substation | 900 € |

In this chapter, control algorithms used to control aggregated heating ventilation and air conditioning (HVAC) units and battery energy storage system (BESS) for the upgrade deferral of grid-side transmission structure are introduced. Two separate cases are investigated over the constructed scenario;

- **Case 1:** Projected industrial electricity consumption increase ratio is applied to the industrial load.

- **Case 2:** A block addition is defined for the wind farm capacity.

The effects of DSM and ESS control methods are analyzed for the upgrade deferral of the existing grid-side transmission structure for both cases, using the obtained simulation results. The chapter is concluded with the interpretation of the simulation results.

### 4.2 Specifications

### 4.2.1 Demand Side Management

In this study, constant speed heatin ventilation and air conditioning (HVAC) units are chosen as the aggregated load to be controlled. Constant speed HVAC units, unlike HVAC units with inverter technologies, can only operate at full power. Depending on the specific conditions, HVAC units can operate either in cooling mode or heating mode. In order to define HVAC units' specifications, different catalogs are examined and compared. A datasheet of typical constant speed casette type HVAC unit used in the small to medium-sized office buildings is shown in Fig. 31 [43]. Using the information on this datasheet, input power of the HVAC units is defined as 1.80 kW and 1.90 kW for cooling and heating modes, respectively. Energy efficiency ratio (EER) which corresponds to cooling power ratio and coefficient of performance (COP) which corresponds to heating power ratio are defined as 2.74 and 2.83, respectively.

| Model No. | Indoor unit | | AUY18ABAB | AUY18RBAB |
|---|---|---|---|---|
| | Outdoor unit | | AOY18ANCKL | AOY18RNCKL |
| Power Source | | V/Ø/Hz | 220-240/1/50 | 220-240/1/50 |
| Capacity | Cooling | kW | 4.95-5.10 | 4.85-5.00 |
| | | BTU/h | 16,900-17,400 | 16,600-17,100 |
| | Heating | kW | — | 5.30-5.45 |
| | | BTU/h | — | 18,100-18,600 |
| Input Power | Cooling/Heating | kW | 1.80-1.90 / — | 1.75-1.85 / 1.85-1.95 |
| EER | Cooling | W/W | 2.75-2.68 | 2.77-2.70 |
| COP | Heating | | — | 2.86-2.79 |
| Running Current | Cooling/Heating | A | 8.50-8.00 | 8.5-8.0 / 9.0-8.5 |
| Moisture Removal | | l/h | 2.1 | 2.1 |
| Sound Pressure | Indoor (High) | dB(A) | 44 | 44 |
| | Outdoor | | 52 | 52 |
| Airflow Rate (High) | Indoor | $m^3/h$ | 650 | 650 |
| | Outdoor | | 3,500 | 3,500 |
| Net Dimension H×W×D Net Weight | Indoor | mm | 235x580x580+70 | 235x580x580+70 |
| | | kg(lbs) | 18.0 (40) | 18.0 (40) |
| | Outdoor | mm | 650x830x320 | 650x830x320 |
| | | kg(lbs) | 51.0 (112) | 56.0 (123) |
| Piping Connections (Small / Large) | | mm | 6.35/12.70 | 6.35/12.70 |
| Drain Pipe Diameter (I.D./O.D.) | | | 25.0/32.0 | 25.0/32.0 |
| Max Pipe Length (Pre-Charge) | | m | 20(7.5) | 20(10) |
| Max Height Difference | | | 8 | 8 |
| Operation Range | Cooling | °CDB | 10 to 43 | 10 to 43 |
| | Heating | | — | -5 to 24 |
| Refrigerant | | | R22 | R22 |
| Cassette Grille | | | UTG-UDYD-W | UTG-UDYD-W |

Fig. 31: Datasheet of a constant speed HVAC unit [43]

Thermal capacitance and thermal resistance of the equivalent thermal model used to model room temperature dynamics are chosen as 9,200 kJ/ºC and 50 ºC/kW, respectively as presented in [44]. Using these parameters for the equivalent thermal model, temperature of a room can be decreased/increased about 1 ºC from ideal room temperature in approximately 30 minutes when the HVAC units operate, assuming 23 ºC ambient temperature.

10,000 HVAC units are defined for the organized industrial zone and HVAC units divided into 50 groups with 200 HVAC units each, in order to control the HVAC load with less than 0.5 MW step. Full load of the HVAC units occupy approximately 12% of the maximum industrial load.

### 4.2.2 Battery Energy Storage System

Main battery energy storage (BESS) specifications; rated power and energy to power ratio, are defined differently for two separate cases, according to the system needs, analyzing the power flow characteristics on the grid-side transmission structure. Charging and discharging limits of the BESS are defined as the rated power of the BESS. State of charge (SoC) limits for the BESS is chosen as 0.30 and 0.90 in order to extend the lifetime of the battery [47], so available storage capacity of the BESS is limited to 60% of the total capacity. Considering the battery and converter losses, efficiency of both charging and discharging cycle is defined as 93% with an overall efficiency of 86.5%.

Three components are included for the investment costs of the BESS; the power conversion system costs ($C_{PCS}$) corresponding to power electronics equipment expressed per unit of BESS rated power (€/kW), the energy storage unit costs ($C_S$) corresponding to battery expressed per unit of BESS storage capacity (€/kWh) and the balance of plant costs ($C_{BoP}$) corresponding to other services (engineering, grid connection, etc.) expressed per unit of BESS storage capacity (€/kWh). Approximate investment costs of lead-acid and lithium-ion type BESSs are tabulated at Table 16 [48].

Table 16: Approximate investment costs of BESSs with lead-acid and lithium-ion battery technologies [48]

| Cost parameters | Lead-acid | Lithium-ion |
|---|---|---|
| Power conversion system (per kW) | € 150 | € 150 |
| Energy storage system (per kWh) | € 125 | € 450 |
| Balance of plant (per kWh) | € 45 | € 25 |

## 4.3 Control Algorithms

### 4.3.1 Control of HVAC Units

Without demand-side management (DSM) control method, heating, ventilation and air conditioning (HVAC) units are controlled simply by local controllers, using predefined temperature limits set by thermal comfort zone of the rooms and critical temperature limits change between cooling and heating operation modes. Total load of the HVAC units without the DSM control is defined as the base load of HVAC units and extracted from the industrial load data in order to find the organized industrial zone power consumption without the usage of the HVAC units.

For the DSM application, a central controller is defined over the local controllers. Direct control method is chosen to control the aggregated load of the HVAC units; the set power is calculated for every time step and sent to units in order to manage the demand-side efficiently according to grid needs. Flowcharts of central controller and local controller algorithms are presented in Fig. 32 and Fig. 33, respectively. Flowchart of overall control algorithm is also presented in Fig. 34.

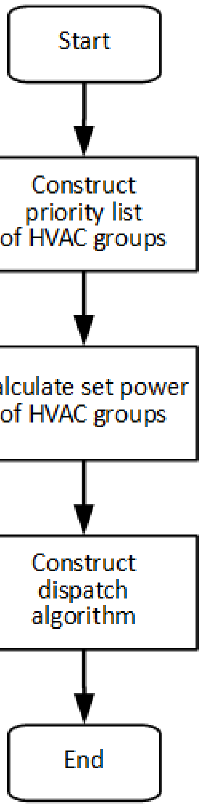


Fig. 32: Flowchart of HVAC central controller algorithm

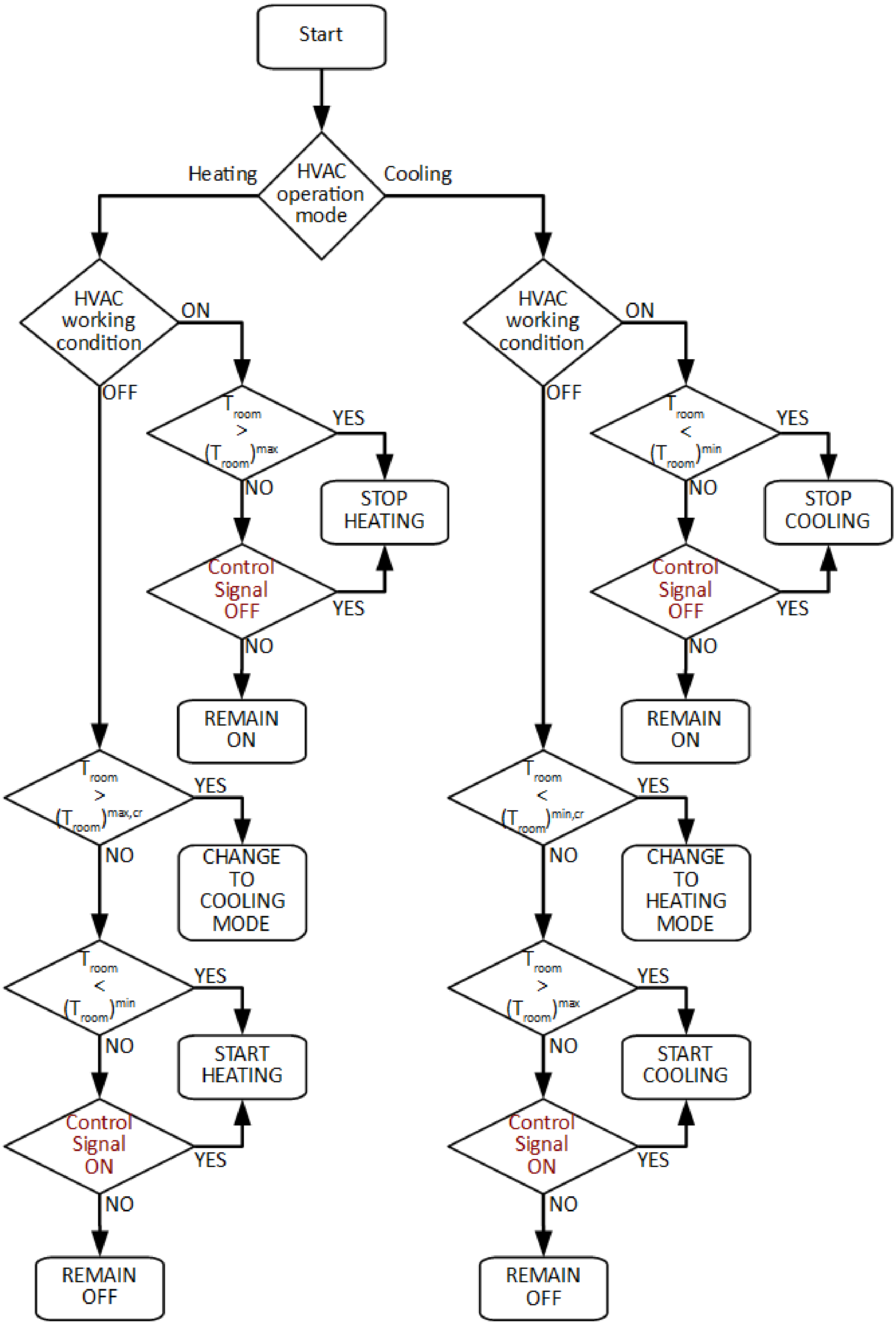


Fig. 33: Flowchart of HVAC local controller algorithm

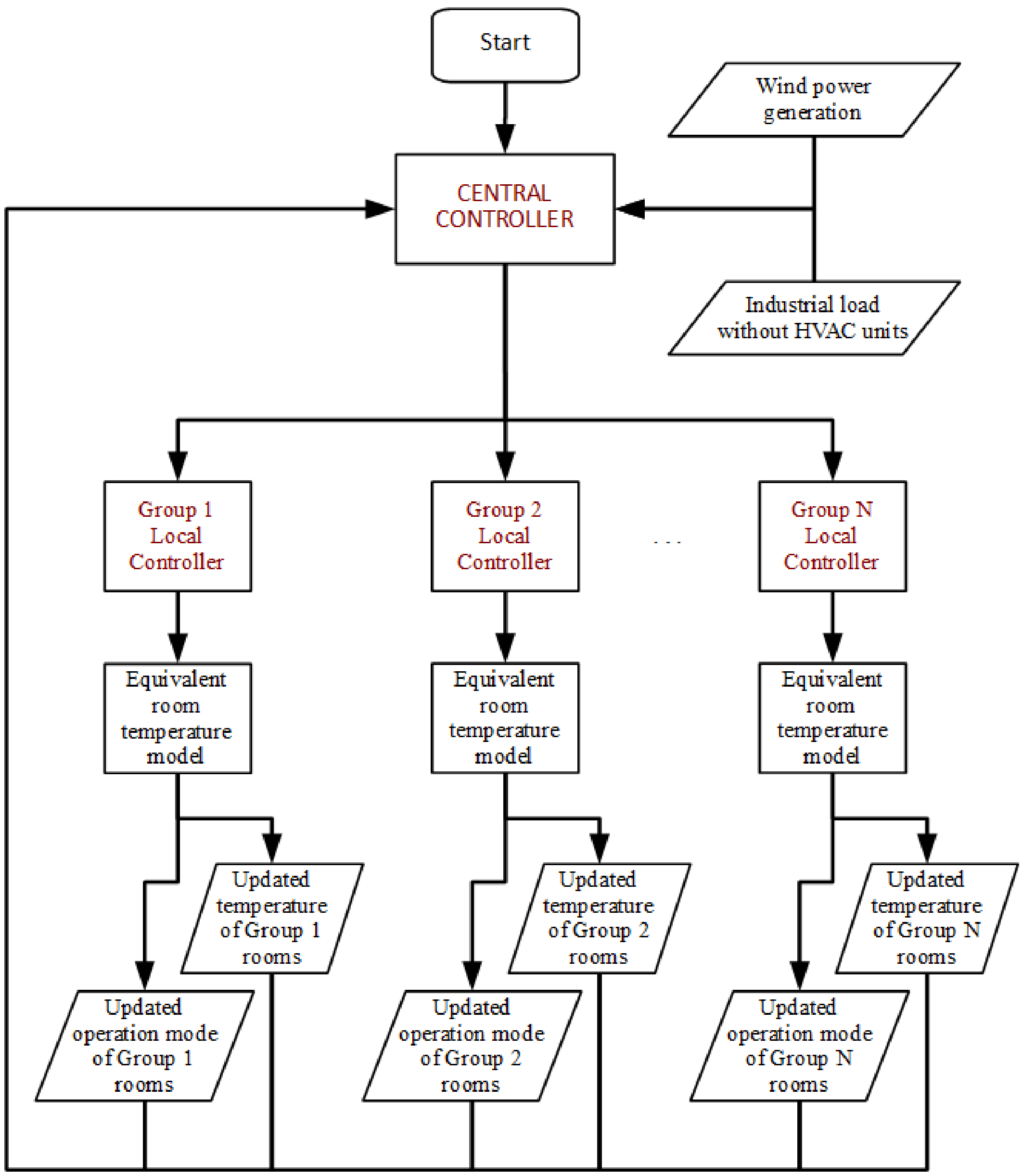


Fig. 34: Flowchart of DSM algorithm

The calculations and decisions of DSM algorithm at every time step can be summarized as follows:

- Central controller calculates the set power for the total HVAC load by using the wind power generation and industrial load data (extracting the base load of HVAC units) information and taking the transmission-side capacity into account.

- Central controller creates the priority list for HVAC groups by using HVAC operation mode and room temperature information sent from local controllers.

- Central controller constructs the dispatch algorithm, combining calculated set power and created priority list. Dispatch signals are sent to all local controllers.

- Local controllers dispatch the HVAC groups according to control signals sent from central controller, provided that temperature limits of the thermal comfort zone are not exceeded.

- Operation mode of the HVAC groups and room temperatures are updated for the next time step using the equivalent thermal model, and these information sent back to central controller.

### 4.3.2 Control of BESS

In order to maintain the power flow on the grid-side between the limits of transmission capacity, battery energy storage system (BESS) is controlled according to grid requirements where demand-side management (DSM) control cannot meet the intended operation. Flowchart of BESS control algorithm is presented in Fig. 35.

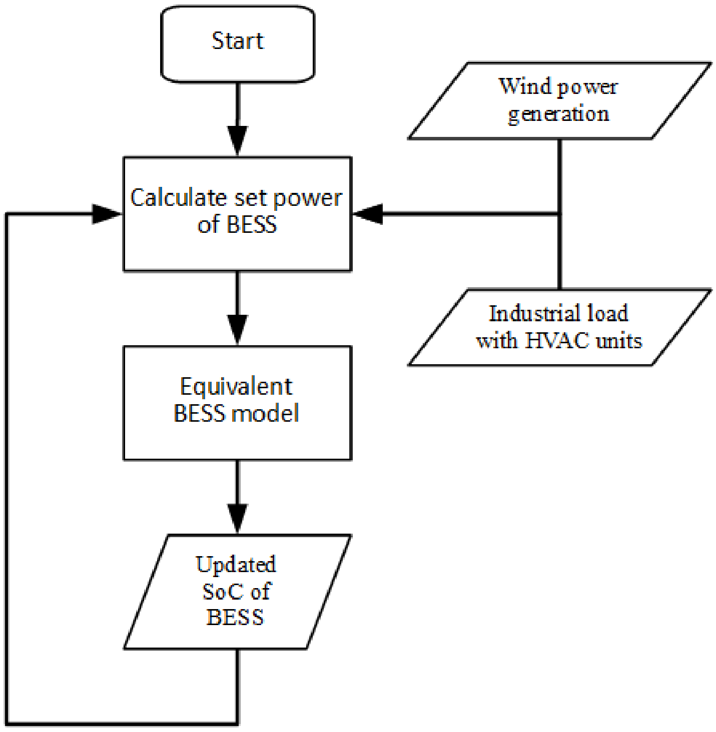


Fig. 35: Flowchart of BESS control algorithm

The calculations and decisions of BESS control algorithm at every time step can be summarized as follows:

- The BESS controller calculates the set power for the BESS by using the wind power generation and total industrial power consumption, also considering state of charge (SoC) of the BESS.

- BESS is operated according to calculated set power, either in charge or discharge mode.

- SoC of the BESS is updated according to equivalent BESS model and sent back to the BESS controller.

## 4.4 Cases

### 4.4.1 Case 1 – Industrial Growth

As a result of ongoing industrial development in Turkey, electricity consumption increases over the years, which leads shortcoming in the present power system structures. Total and industrial energy consumption of Turkey between 2006 and 2015 are tabulated at Table 17, which are taken from the database of Turkish Statistical Institute (TÜİK, in native initials) [49]. Increase in both total and industrial electricity consumption can be observed throughout the years but 2009, which can be interpreted as a consequence of global financial crisis in 2008.

Table 17: Total and industrial electricity consumption throughout the years [49]

| Year | Total Electricity Consumption (GWh) | Industrial Electricity Consumption (GWh) | Total Electricity Consumption Change (%) | Industrial Electricity Consumption Change (%) |
|---|---|---|---|---|
| **2006** | 143.07 | 67.96 | 10.03 | 8.38 |
| **2007** | 155.14 | 73.84 | 8.44 | 7.97 |
| **2008** | 161.95 | 74.82 | 4.39 | 1.30 |
| **2009** | 156.89 | 70.45 | -3.12 | -6.21 |
| **2010** | 172.05 | 79.31 | 9.66 | 11.18 |
| **2011** | 186.10 | 88.03 | 8.17 | 9.89 |
| **2012** | 194.92 | 92.39 | 4.74 | 4.73 |
| **2013** | 198.05 | 93.28 | 1.61 | 0.95 |
| **2014** | 207.38 | 97.88 | 4.71 | 4.70 |
| **2015** | 217.31 | 103.44 | 4.79 | 5.37 |

In the Electricity Demand Projection Report prepared by Republic of Turkey Ministry of Energy and Natural Resources, electricity consumption for 3 scenarios (low, reference and high consumption) are tabulated for the next 20 years, which are shown in Fig. 36 [50]. In this report, yearly electricity consumption projection results for 3 scenarios are calculated as 3.5%, 4.2% and 5.3%, respectively.


Fig. 36: Projection of electricity consumption in Turkey for the next 20 years [50]

Using aforementioned electricity consumption increase percentages on organized industrial zone data chosen for this study, maximum power demand on the transmission line for 3 different scenarios are tabulated at Table 18 and plotted in Fig. 37. For the chosen transmission line structure (182 MVA) and 5% safety margin, overload on the transmission occurs;

- In 2021 for 3.5% industrial load increase
- In 2020 for 4.2% industrial load increase
- In 2019 for 5.3% industrial load increase

These results show the transmission system defined in the constructed scenario will need an upgrade in just 2-4 years (depending on the demand growth). In the simulations, The base scenario with 4.2% yearly increase of industrial load is used. Maximum overloads on the grid-side transmission structure for the base scenario in 2021, 2022 and 2023 are plotted in Fig. 38.

Table 18: Maximum projected power flow on the grid-side transmission structure for next 10 years

| Year | Scenario 1 – 3.5% (MW) | Scenario 2 – 4.2% (MW) | Scenario 3 – 5.3% (MW) |
|---|---|---|---|
| **2017** | 155.01 | 156.06 | 157.70 |
| **2018** | 160.43 | 162.61 | 166.06 |
| **2019** | 166.04 | 169.44 | 174.86 |
| **2020** | 171.86 | 176.56 | 184.13 |
| **2021** | 177.88 | 183.97 | 193.89 |
| **2022** | 184.10 | 191.70 | 204.17 |
| **2023** | 190.55 | 199.75 | 215.00 |
| **2024** | 197.22 | 208.14 | 226.43 |
| **2025** | 204.12 | 216.90 | 238.45 |
| **2026** | 211.27 | 226.03 | 251.12 |

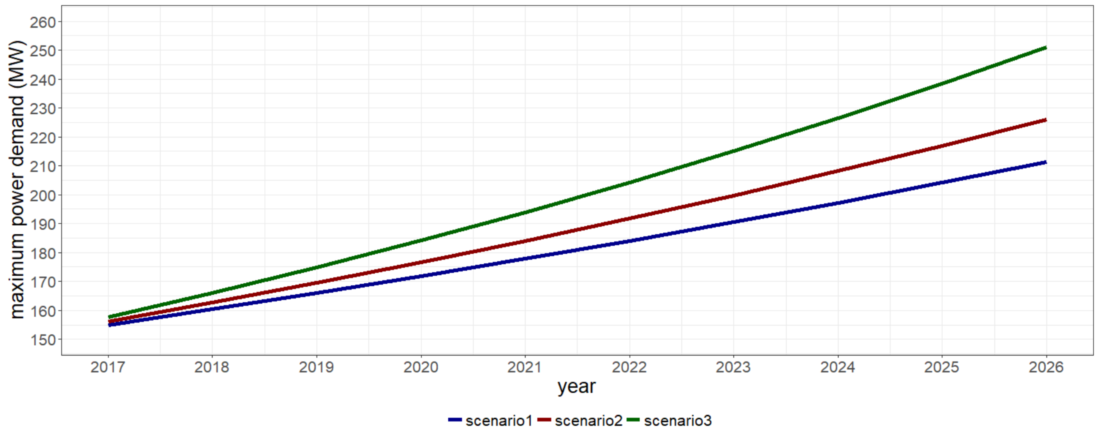


Fig. 37: Maximum projected power demand on the grid-side transmission structure for next 10 years

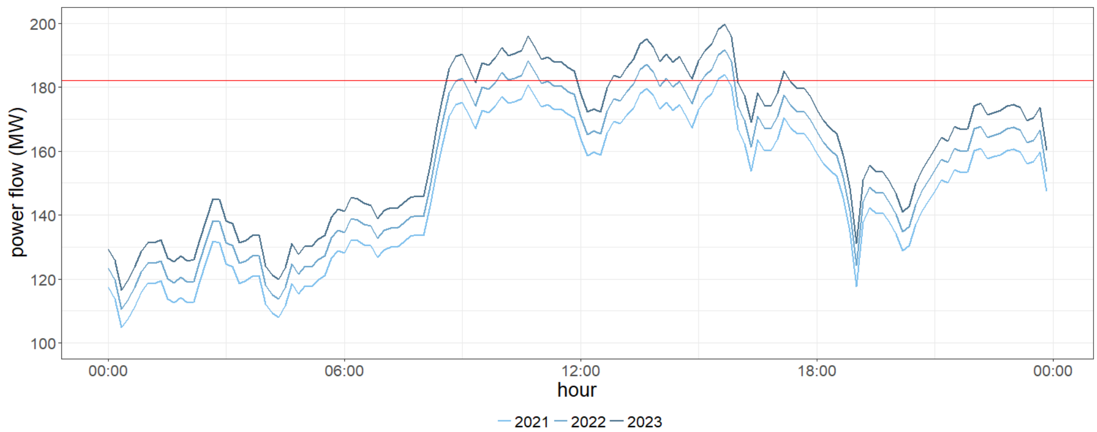


Fig. 38: Overload on the grid-side transmission structure

Using the present generation and load data with 4.2% increase on the industrial load, maximum overload on the grid-side transmission structure in 2020 is projected with approximately 176.5 MW. Taking the 5% safety margin defined for the transmission structures into account, maximum excess power flow over the grid-side transmission structure is approximately 3.6 MW and power demand from the grid exceeds the capacity of transmission structure with a maximum of 3 time-step (30 minutes) interval.

As mentioned before, total load of the heating, ventilation and air conditioning (HVAC) units is chosen approximately as 12% of the total industrial load. Using the defined increase ratio on the industrial load, full load of the HVAC units is also increased with a ratio of 18% for this case. With this increase ratio, the full load capacity of the HVAC units becomes approximately 22.5 MW, which is sufficient to absorb the excess power in normal conditions. However, it is important to note that this capacity can be unavailable for the critical intervals, as the thermal comfort of the room limits the control over HVAC units. With this analysis, it is suitable to choose the BESS with 4 MW rated power and 2 MWh storage capacity (0.5 hours energy to power ratio), in order to maintain power flow on the grid-side between the limits of transmission capacity throughout the year.

Power flow on the grid-side with the control algorithm is shown in Fig. 39. As it can be observed from this figure, excess power flow on the grid-side is prevented and power flow is maintained in the safe zone (which is defined as the 95% of the capacity of existing transmission structure). Power output of the HVAC units and corresponding room temperatures are presented in Fig. 40 and Fig. 41. As it can be seen from these figures, HVAC units are operated considering grid needs, as long as the room temperatures between 22-24 ºC. Power output and state of charge (SoC) of the BESS are also presented in Fig. 42 and Fig. 43. SoC of the BESS is kept between 0.3 and 0.9 all the time, in order to extend the battery life. From these figures, it can be observed that the BESS is idle most of the time and operated when the load of the HVAC units are insufficient to keep power flow on the safe zone. Usage of the BESS can be made more effective by adding complementary uses and benefits to the control algorithm, which will be discussed later in this chapter.

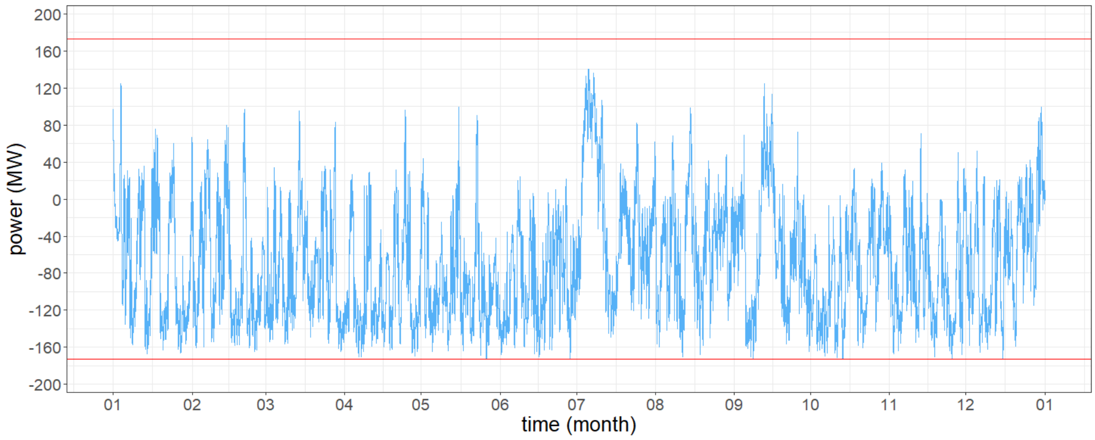


Fig. 39: Power flow on the grid-side transmission structure with the control algorithm for Case 1

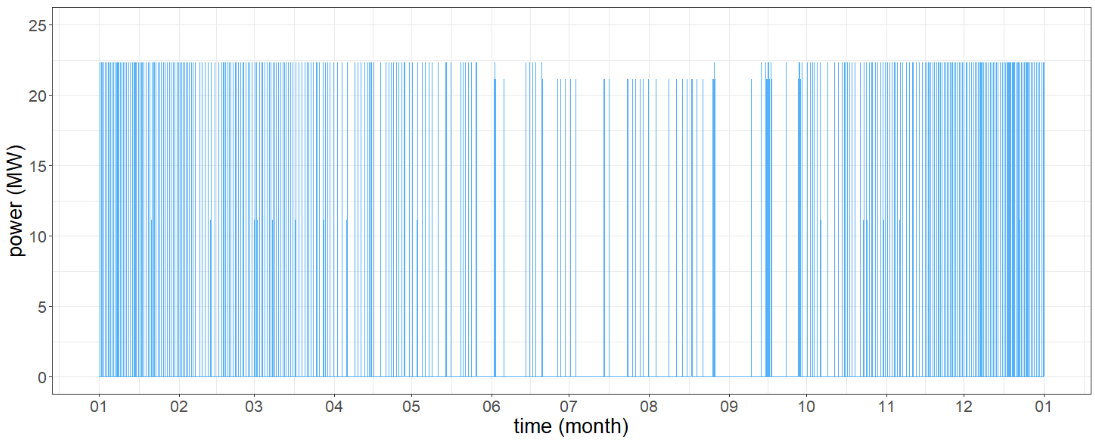


Fig. 40: Power output of the HVAC units for Case 1

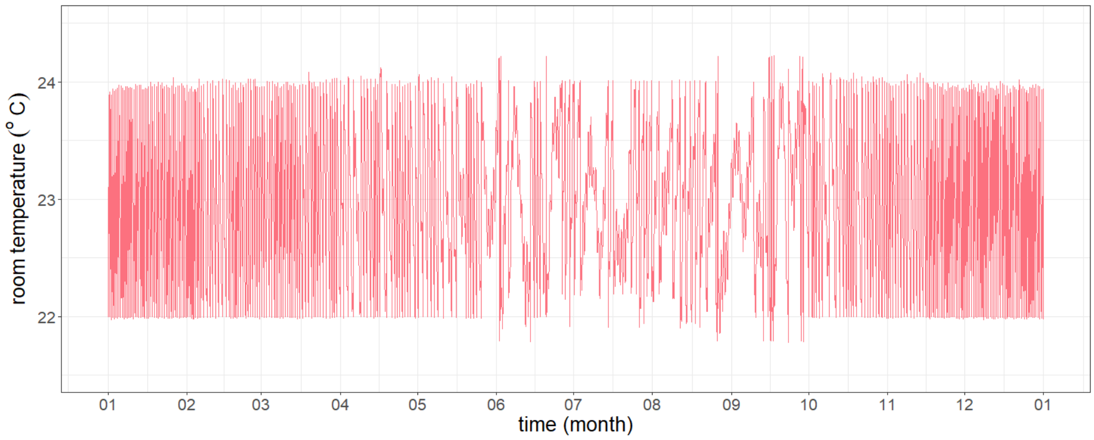


Fig. 41: Room temperatures of the corresponding HVAC units for Case 1

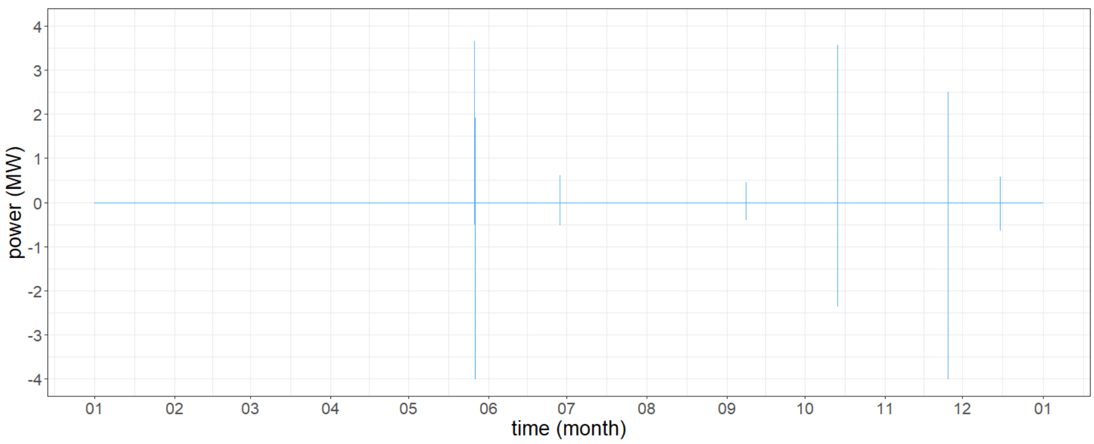


Fig. 42: Power output of the BESS for Case 1

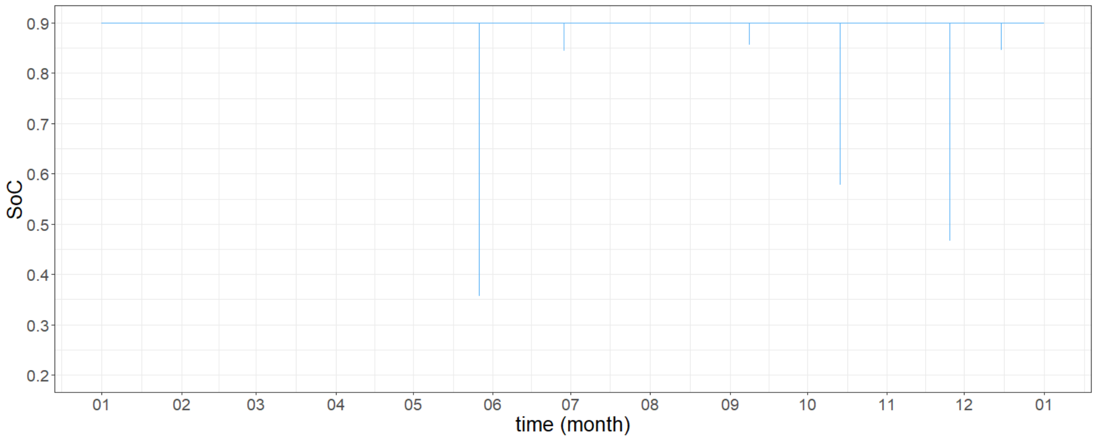


Fig. 43: SoC of the BESS for Case 1

Capital expenditure (CAPEX) of a new transmission structure in case of an overload depends on the length of the transmission line. For this study, length of the transmission line is taken as 25 km, by taking the transmission structure of chosen wind farm into account. With this information, CAPEX of a new transmission line (182 MVA rating) with the power transformers and protection and control equipments (200 MVA rating) on both sides of the line becomes **€ 3,030,000**. CAPEX of the BESS in industrial load increase case for one-year deferral application is calculated as **€ 940,000** for lead-acid batteries and **€ 1,550,000** for lithium-ion batteries.

In order to convert total capital cost of the BESS and transmission structures to annualized cost, fixed charge rate (FCR) is used. FCR of the transmission structure is taken as 11% [38] and FCR of the BESS is taken as 12% [51]. With chosen FCR values, annual cost of the transmission structure becomes **€ 333,300** and annual cost of the BESS becomes **€ 112,800** for lead-acid batteries and **€ 186,000** for lithium-ion batteries.

Power flow on the grid-side is also analyzed for the second year deferral of the transmission structure upgrade for this case. In 2022, maximum excess power flow over the grid-side transmission structure is calculated as approximately 11 MW. In order to keep power flow on the safe zone for a second year deferral, a 12 MW rated power BESS with 18 MWh storage capacity (1.5 hours energy to power ratio) is needed. It is important to note that, usable capacity of the BESS is 10.8 MWh as the SoC is limited between 0.3 and 0.9. Power output and SoC of the BESS for the second year deferral are presented in Fig. 44 and Fig. 45. It can be observed from these figures that the BESS is operated more often compared to the first year deferral case, but still stays in idle mode most of the time.

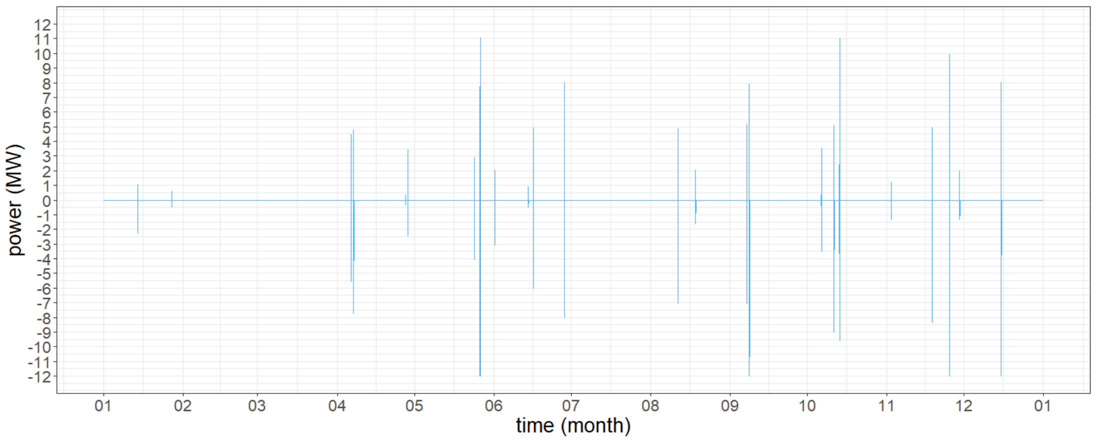


Fig. 44: Power output of the BESS for Case 1 (second year deferral)

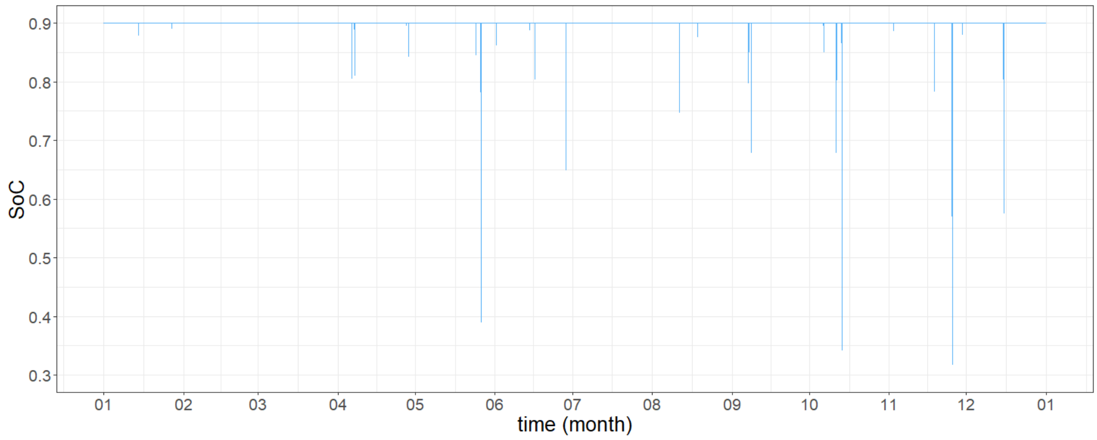


Fig. 45: SoC of the BESS for Case 1 (second year deferral)

For the second year deferral, CAPEX of the BESS with increased capacity is calculated as **€ 4,800,000** and **€ 10,350,000** for lead-acid and lithium-ion battery types, respectively. Using the FCR, annual costs become **€ 576,000** and **€ 1,242,000**, respectively. Considering the annual cost of transmission structure, **€ 333,300**, second year deferral of the transmission-side upgrade is concluded as infeasible for the transmission structure with chosen transmission length (25 km).

Length of the transmission line is another important factor for the feasibility analysis. For every 5 km increase on the line length, **€ 182,000** is added to transmission line CAPEX as the power transformer and substation costs are independent of the line length. Using this information, minimum transmission length for a feasible second year deferral is calculated as 90 km for the lead-acid battery type and 255 km for the lithium-ion battery type. These calculated lengths can be used to have a general idea on the overall situation.

#### 4.4.2 Case 2 – Wind Farm Block Addition

Installed wind energy capacity in Turkey has been increasing over the years in a similar to the global trend. Considering the growing trend on the wind energy, a block addition is defined on the wind farm for the second case, which will lead the power flow on the transmission structure over the capacity of the structure. Maximum projected power on the grid-side transmission structure is tabulated for different block additions on the wind farm at Table 19. Considering the installed wind energy capacity increase rates in Turkey for the last 10 years [4], 25% capacity increase on the wind farm is found appropriate for this case.

Table 19: Maximum projected power on the grid-side transmission structure for different block additions on the wind farm

| Percentage | Scenario (MW) |
|---|---|
| **10%** | 157.70 |
| **15%** | 165.35 |
| **20%** | 173.01 |
| **25%** | 180.66 |
| **30%** | 188.31 |
| **35%** | 195.97 |

Using the present generation and load data with 25% increase on the wind generation, maximum overload on the grid-side transmission structure is projected approximately 180.7 MW. Taking the 5% safety margin into account, maximum excess power flow over the grid-side transmission structure is approximately 7.8 MW and power demand from the grid exceeds the capacity of transmission structure with a maximum of 5 time-step (50 minutes) interval. As stated before, heating, ventilation and air conditioning (HVAC) units cannot contribute to the support of the grid needs in some situations, as certain boundaries are defined for the thermal comfort of the rooms. Taking the worst case situation into account, it is suitable to choose the battery energy storage system (BESS) with 9 MW rated power with 4.5 MWh storage capacity (0.5 hours energy to power ratio).

Power flow on the grid-side with the control algorithm for this case is shown in Fig. 46. As it can be observed from this figure, excess power flow on the grid-side is prevented and power flow is maintained in the safe zone (which is defined as the 95% of the capacity of existing transmission structure). For this case, BESS usage is limited to a very narrow region, where the wind power generation peaks and industrial load stays low for approximately 2 hours. It is important to point out that HVAC loads cannot support the grid needs in that period because of two main reasons; either they work on full load condition or some HVAC groups cannot work in order to maintain temperature comfort zones of the rooms.

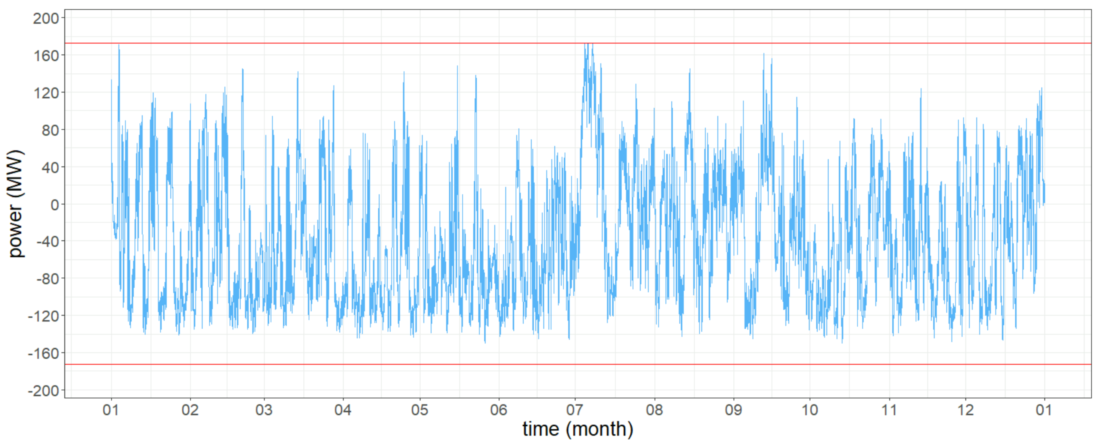


Fig. 46: Power flow on the grid-side transmission structure with the control algorithm for Case 2

Capital expenditure (CAPEX) of the new transmission structure in case of an overload for defined 25 km length is **€ 3,030,000**, as calculated in the previous case. For a 25% wind generation capacity increase, CAPEX of the BESS for the deferral application is calculated as **€ 2,115,000** for lead-acid batteries and **€ 3,487,500** for lithium-ion batteries.

Using the FCR values presented in the previous case, annual cost of the transmission structure is **€ 333,300** and annual cost of the BESS becomes **€ 253,800** for lead-acid batteries and **€ 418,500** for lithium-ion batteries. For the defined 25% wind generation capacity increase, deferral of the transmission structure upgrade can be applied by using lead-acid type BESS. Above 25% block additions to wind generation, total capital cost of the BESS will increase extremely because of the high storage capacity need, which will make the deferral application infeasible for the analyzed case.

### 4.5 Complementary Uses of the BESS

For the both cases analyzed in this study, battery energy storage (BESS) operates only for short intervals and stays in the idle mode for the most of the time. Because of the infeasibility of idle usage of the BESS, it is important to add complementary uses and benefits, which can compensate the high capital expenses and increase the applicability of the proposed method. However, complementary uses should not conflict with the transmission capacity related application and should add value to the benefits came from the primary use of the BESS. Complementary uses which can be added to the main purpose of the storage system can be summarized as follows [38]:

- **Wholesale electric energy time-shift:**
  By storing the energy when the market price is low and selling the stored energy with higher price, time-shifting can be profitable for the suppliers.

- **Voltage (reactive power) support:**
  Voltage stability of a grid can be increased with BESS; using the converters to support the reactive power need.

- **Electricity service reliability:**
  Reliability of the transmission of electric power from suppliers to end-users can be increased, by using BESS to support the grid in case of emergencies.

- **Electric supply capacity:**
  The cost of generation equipment can be reduced by using energy storage, simply by storing the energy when the load is low and releasing the stored energy when the load exceeds generation capacity. By doing so, generation power need can be reduced equal to the amount of storage power.

- **Seasonal deployment:**
  By analyzing the seasonal trends of a grid, BESS can be used to store the energy when there is excess generation and release the stored energy later when needed.

- **Retail time-of-use energy cost reduction:**
  Electric energy pricing changes according to peak and off-peak hours. Storing the energy in low price periods and using this energy when demand and price are high can be profitable for the end-user.

- **Renewable energy time-shift:**
  Renewable generation is not controllable but can be stored at off-peak periods by using BESS and stored energy can be used later at peak periods, when energy prices are high.

For this study, BESS is operated for smoothing out the wind farm power output, when it is sufficient to do so. Block addition to the wind power generation is analyzed for the complementary usage of the BESS. As it is very important to maintain the main control of the BESS when it is needed, complementary application is limited for the certain area; where the power flow on the grid-side is between critical limits. When these limits are exceeded, BESS is prepared for the upgrade deferral operation and waited as long as power flow drops below the critical limits. With the simulation results, it is observed that power flow is maintained in the safe zone so the addition to the BESS control algorithm does not effect the main purpose of this study. Using the available capacity of the BESS, fluctuations on the wind power generation is tried to be smoothed. Wind power generation of a 6 hours period before and after the complementary usage of the BESS are shown in Fig. 47. Power output and state of charge (SoC) of the BESS after the addition of complementary usage for the same time interval are also plotted in Fig. 48 and Fig. 49. It can be observed from these figures that the BESS supports the wind generation on the fluctuations when its capacity is sufficient.

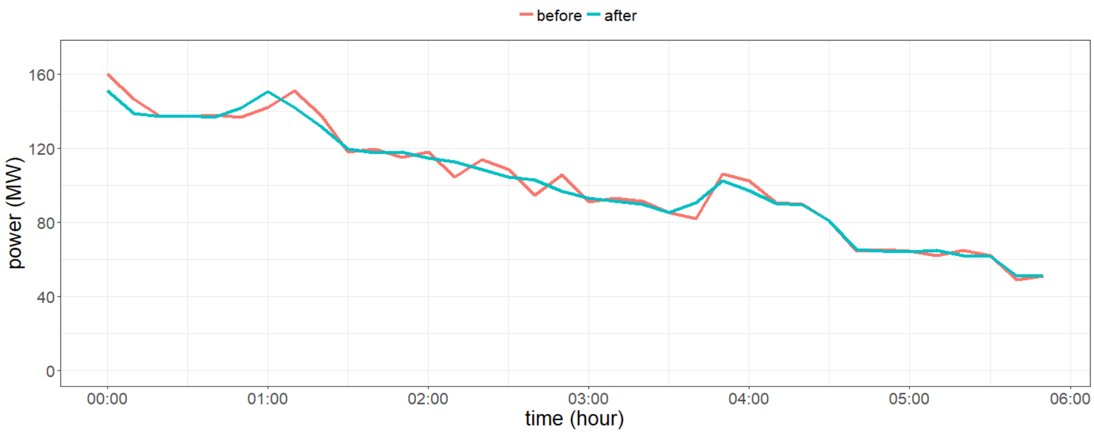


Fig. 47: Wind power generation output before and after complementary usage of the BESS

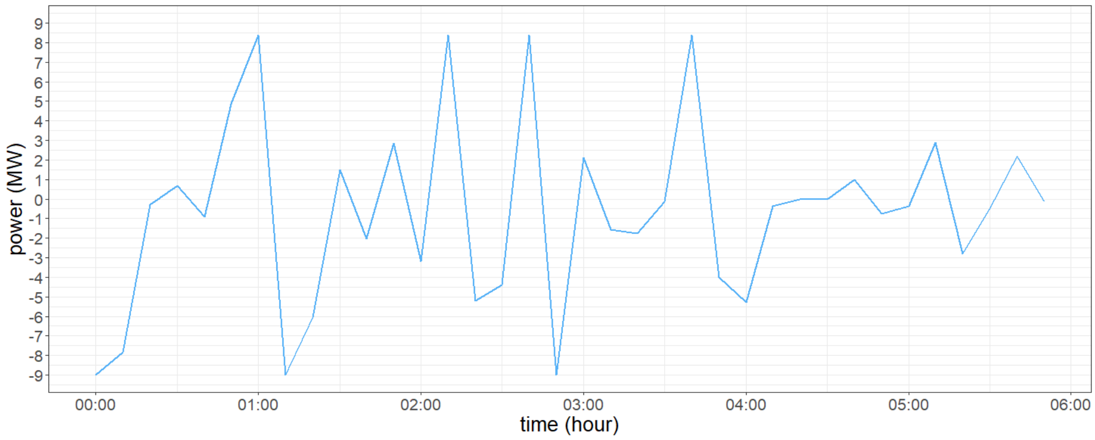


Fig. 48: Power output of the BESS after the addition of complementary usage

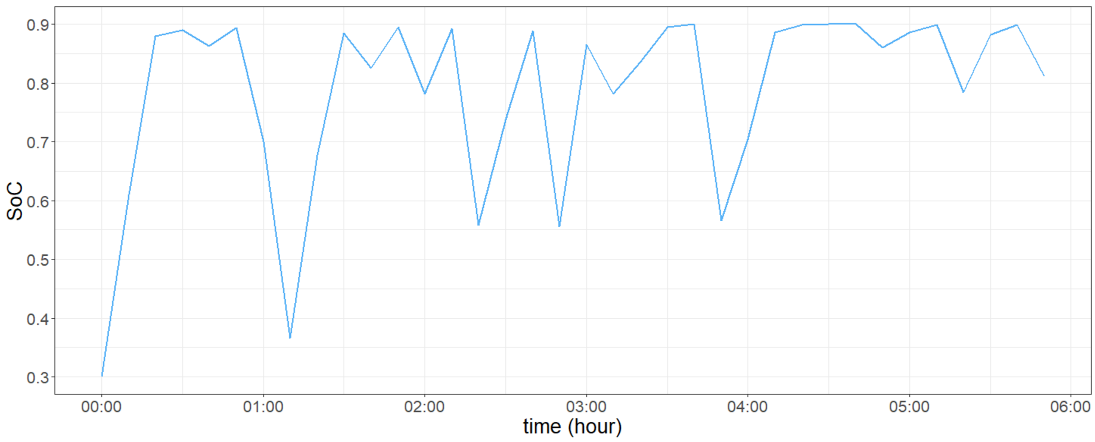


Fig. 49: SoC of the BESS after the addition of complementary usage

### 4.6 Summary and Conclusion

In this chapter, the effects of demand-side management (DSM) control on the heating, ventilation and air conditioning (HVAC) units and battery energy storage (BESS) control are investigated for the constructed scenario and control algorithms are explained for the upgrade deferral application. Two different cases are defined for the specific scenario; increase on the industrial load and block addition to the wind generation. Simulation results are presented and commented for both cases. Economical analysis on the simulation results are also done using the approximate capital costs. Overall results of cost analysis for both cases are tabulated at Table 20.

Table 20: Overall results of the cost analysis

| | **Case 1 (year)** | | **Case 2 (increase)** |
|---|---|---|---|
| | **1 year** | **2 years** | **25%** |
| **Transmission stucture** | € 333,300 | | |
| **Lead-acid type BESS** | € 112,800 | € 576,000 | € 253,800 |
| **Lithium-ion type BESS** | € 186,000 | € 1,242,000 | € 418,500 |

It is concluded that the deferral of the transmission structure upgrade becomes infeasible after 1 year deferral for the Case 1 and beyond 25% wind capacity increase for Case 2 for the constructed scenario. However, using the BESS with complementary uses as long as the main control purpose is not contradicted, can add value to this specific application, which is also investigated in this chapter.

As the BESS can only support the grid needs for the upgrade deferral applications in a limited way, the operation of the BESS is limited for a short interval. An approach to this problem is redeployable BESSs which are modular and transportable [38]. Modular BESS with lithium-ion technology up to 100 MW rated power and 200 MWh storage capacity is commercially available and an example of a single module up to 2.1 MW rated power and 2.4 MWh storage capacity is shown in Fig. 50 [52]. This system includes the batteries, controls, protection cabinets and transformers. The dimensions of the given system is 13.56x2.35x2.7m (WxDxH) and weights 35 to 45 tons; which can be transferred by semi-trailer trucks, as proposed. An example of these modular BESS are installed in Hawaii, with 6 MW rated power and 4.63 MWh storage capacity, integrated to a 12 MW solar photovoltaic plant [53]. For the aforementioned system, the main objects are the smoothing the solar power output for grid integration and frequency regulation. It is important note that the rated power of the BESS integrated to this system is 50% of the rated power of the solar plant. In this study, storage capacity is kept as low as possible, approximately %4.4 of the wind generation capacity in the defined case with the complementary usage of the BESS, in order to lower the capital costs.

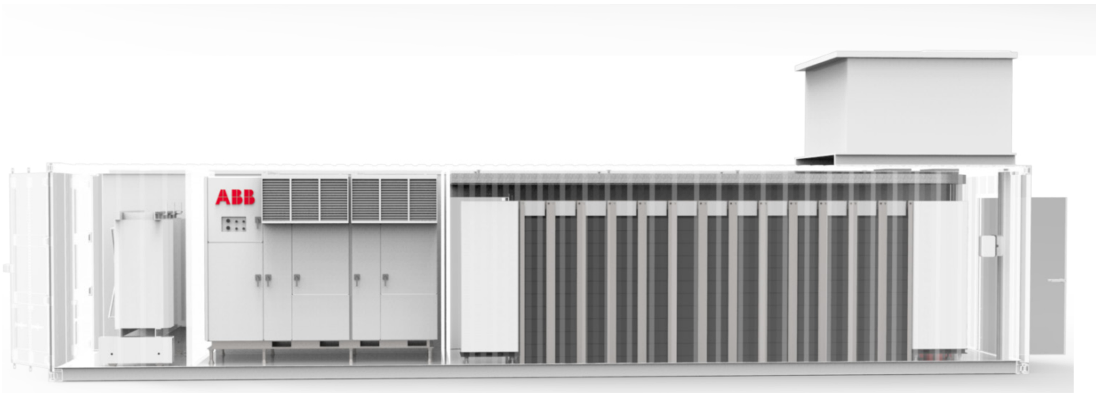


Fig. 50: Typical BESS module [52]

Using modular and transportable BESS can be a great advantage for the overall power system, as the BESS modules can be transferred where they are needed. When the operation of a BESS becomes infeasible for a region, modules can be redeployed for different regions, which can be determined by proper power system analysis. By using this method, BESS modules can be used for upgrade deferral application of several regions, but not restricted with this specific application only.

# CHAPTER 5

# CONCLUSION AND FUTURE WORKS

In this thesis, effects of energy storage systems (ESSs) and demand-side management (DSM) are examined for the transmission structure upgrade deferral application in the presence of wind power generation.

In the beginning, characteristics of ESSs and aggregated loads for DSM applications are analyzed for the specific application. Considering the large-scale energy storage requirement for the wind integration applications, battery energy storage system (BESS), pumped hydro system (PHS) and compressed air storage system (CAES) technologies are found suitable for the study. By taking the topographical constraints of PHS and CAES technologies into account, BESS technology is chosen for this study [5]. Comparing the advantages and disadvantages of battery types, lithium-ion and lead-acid batteries are investigated due to their high energy and power density, fast charge and discharge capability, long life time and high efficiency [24]. For the DSM application, constant speed heating, ventilation and air conditioning (HVAC) units are chosen as the aggregated load, considering the high percentage energy usage in residential and commercial areas (in United States, approximately 50% of the total energy consumption in residential sector and 25% of the total energy consumption in commercial sector, in 2016 [32]). Two-way communication direct control method is selected to control the aggregated load; HVAC units are controlled by a central controller, local controllers acknowledge the specific commands sent to them and send applicability information back to the controller [34].

With the selection of storage technology and controllable load, a hypothetical scenario is constructed, where a wind farm is connected to a nearby organized industrial zone with the transmission structures. Wind power generation and organized industrial zone load data are obtained from Monitoring and System Development for Wind Generated Electrical Power in Turkey (RİTM, in native initials) and National Power Quality Project (MGKP, in native initials) of The Scientific and Technological Research Council of Turkey, Marmara Research Center, Energy Institute (TÜBİTAK MAM EE, in native initials). Obtained raw data from databases of the aforementioned projects are organized and processed using R. Data used in this study are acquired in 2016 with 10 minute intervals. Wind generation data are taken from measurements of a wind farm in the Aegean Region, with 40 MW installed power and 13.2 MW average generation. Industrial load data are taken from measurements of an organized industrial zone in Marmara Region, with 160 MW maximum load and 104.72 MW average consumption. As the high difference between installed wind generation and industrial consumption is undesirable for the constructed scenario, maximum generation and consumption are brought to same level by multiplying wind power generation data by 4.

For the next step, mathematical models are constructed for the simulations. Critical parameters are defined for each model with boundary conditions, which are stated below:

**BESS:** Mode variables of the BESS are defined as idle, discharging and charging modes. Power output is limited to the selected rated power for each case and state of charge (SoC) is maintained between the critical levels.

**HVAC:** HVAC mode variables are defined as idle, heating and cooling modes. Thermal power output of the HVAC units are calculated using coefficient of performance (CoP) of heating mode and energy efficiency ratio (EER) of cooling mode. A simplified model of a resistance-capacitance (RC) circuit analogy is used for temperature dynamics of a space [33], [44]. Thermal comfort of the buildings are maintained between 22-24 C°. In order to include the effects of ambient temperature, U.S. Climate Reference Network (USCRN) database is analyzed, because of the weather data absence of Turkey for subhourly period [45]. Comparing the monthly temperature averages of USCRN database with data of an area in Turkish Aegean Region collected from Turkish State Meteorological Service (MGM, in native initials), suitable data is selected for the study [46].

Considering the constructed scenario, specifications for the transmission line, energy storage and demad-side control are defined. Transmission capacity is defined as 182 MVA (154 kV, 795 MCM conductor type). 10,000 HVAC units are defined for industrial load, combination of 50 groups with 200 HVAC units each. Critical limits for BESS SoC is defined as minimum 0.3 and maximum 0.9, in order to increase the battery life. Taking both the battery and converter losses, efficiency of charging and discharging cycles are defined as 93%, with an overall efficiency of 86.5%. Suitable control methods are developed for both BESS usage and load-side arrangements. These control models are embedded into the simulations in order to observe the affects of the proposed control algorithms.

Two separate cases are investigated; using the projected industrial electricity consumption increase ratio and defining a block addition for the wind farm capacity. For both cases, overload situations on the grid-side transmission structures are analyzed and power flow is tried to be kept between the critical limits (including 5% safety margin) of the transmission line using the capacity of storage system and aggregated loads.

Transmission line length for this study is chosen as 25 km. With this length, capital cost of the transmission structure (including power transformer, substation and transmission line) becomes **€ 3,030,000**. Annualized cost of the transmission structure is **€ 333,300**, using the 11% fixed charge rate (FCR).

- **Case 1 – Industrial Growth**

Using electricity consumption projection results introduced in the Electricity Demand Projection Report prepared by Republic of Turkey Ministry of Energy and Natural Resources on the data selected for the constructed scenario, grid-side transmission load capacity is exceeded in 2020 by approximately 3.6 MW [50]. Total load of the HVAC units is selected as 12% of the maximum industrial load, approximately 22 MW. For this case, BESS rated power is chosen 4 MW with 2 MWh storage capacity, in order to support the maximum loading of the structure when DSM is insufficient to do so.

Capital cost of the BESS with defined specifications is **€ 940,000** for lead-acid type batteries and **€ 1,550,000** for lithium-ion type batteries. Using 12% FCR, annualized costs become **€ 112,800** for lead-acid technology and **€ 186,000** for lithium-ion technology. As seen from these results, deferral of the transmission structure upgrade is profitable for the first year. However, for the second year deferral, 12 MW rated power BESS with 18 MWh storage capacity is needed and the annualized costs of BESS becomes **€ 576,000** and **€ 1,242,000** for lead-acid and lithium-ion batteries, respectively. Comparing these results with annualized cost of transmission structure, it can be seen that the second year deferral is infeasible for this case.

- **Case 2 – Wind Farm Block Addition**

25% block addition on the installed wind generation capacity is defined for this case. After the wind generation capacity increase, overload on the transmission structure becomes 7.8 MW. Total load of the HVAC units is chosen same as first case, 12% of the maximum industrial load, approximately 20 MW in this case. In order to keep the transmission line loading between the critical limits, BESS rated power is chosen 9 MW with 4.5 MWh storage capacity.

Using these specifications, capital cost of the BESS becomes **€ 2,115,000** for lead-acid batteries and **€ 3,487,500** for lithium-ion batteries. Using 12% FCR, annualized costs of lead-acid and lithium-ion type batteries become **€ 253,800** and **€ 418,500**. For defined case, upgrade deferral can be profitable for the lead-acid type batteries. Above 25% wind generation capacity increase, deferral application becomes infeasible as the capital cost of the BESS increases extremely.

Another important observation is that the BESS stays on idle mode most of the time throughout the year in both cases, as it operates when the load of the HVAC units are insufficient to keep the power flow between the limits. In order to increase the applicability of proposed method, BESS usage is not restricted with only transmission upgrade deferral application. For the complementary usage, BESS is operated to smooth out the wind farm power output when it is sufficient to do so. After adding the generation smoothing control, simulations are repeated with the new algorithm in order to check that the main purpose is not affected with the complementary usage. With this modification, BESS is used effectively throughout the year, eliminating low power fluctuations when BESS capacity is sufficient.

Another important factor that need to be take into account is the calculation results of the BESS specifications for defined cases. As the power rating of the BESS is in the range of MW level and after 1 year operation the BESS becomes insufficient for the transmission deferral application, it can be feasible to use modular and transportable BESS. Modular BESS with lithium-ion technology is commercially available up to 100 MW rated power and 200 MWh storage capacity [52]. A single module up to 2.1 MW rated power and 2.4 MWh, dimensions of 13.56x2.35x2.7m (WxDxH) and weights 35 to 45 tons, can be transferred by trucks for the aforementioned systems. Using the modular and transportable BESS, modules can be transferred to several other regions according to grid needs; when the upgrade deferral becomes infeasible in our scenario.

In this study, all simulations are done using real data, and behaviour of battery energy storage system (BESS) and heating, ventilation and air conditioning (HVAC) units are shaped according to instant data. For a better optimization on the storage system and demand side management, forecast algorithms can be applied for power flow and ambient temperature values. In addition to forecasting, complementary usage of the BESS can be modified and different uses can be investigated in order to maximize the feasibility of the systems.

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