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ENERGY SYSTEMS OPERATION AND TECHNOLOGIES

ENERGY MANAGEMENT SYSTEM FOR A RESIDENTIAL MICROGRID WITH A FAST CHARGING STATION

Master Thesis

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ÖZET

HIZLI ŞARJ İSTASYONLU KONUT MİKRO ŞEBEKE İÇİN ENERJİ YÖNETİM SİSTEMİ

Mohammad Albarazi

Enerji Sistemleri İşletim ve Teknolojileri

Tez Danışmanı: Dr. Öğretim Üyesi Gürkan Soykan

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Son zamanlarda, yenilenebilir kaynakların artan kullanımı, elektrikli araç (EV) ve diğer elektrik yüklerinden dolayı yükün büyümesi ve güç elektroniğindeki gelişmeler, güç şebekelerinin mevcut haliyle bu değişikliklere uyum sağlayamaz konuma gelmektedir. Bu nedenle hem yük hem de kaynak tarafında son teknolojileri ve değişiklikleri sistemde kullanmak için yeni yaklaşımlar uygulanmalıdır. Bu çalışmada, iki kısımdan oluşan konut tabanlı bir mikro şebeke için bir enerji yönetim sistemi (EMS) tasarlanmıştır. Bu kısımlardan birincisi, bir fotovoltaik sistem (PV) ve pil depolama sistemi (BSS) içeren bir konut bileşenidir. İkincisi, bir fotovoltaik sistem ve bir süperkapasitör enerji depolama (SCES) içeren bir şarj istasyonudur. Yoğun saatlerde süperkapasitör (SC) kullanımı, elektrikli araçların şarj edilmesi açısından şebeke tarafında yük kaymasını sağlar. Önerilen EMS için bir optimizasyon algoritması uygulanır. Böylece hem SCES hem de BSS, maksimum tüketimin olduğu zamanlarda şarjdan kaçınır. Operasyon senaryolarına göre güç ve maliyetlerde tasarruf sağlanacaktır. Böylece enerji verimliliğinde bir iyileşme sağlanacaktır. Ayrıca, şebeke yoğun zamanlarda fazladan bir aşırı yüklenmeyi önleyecektir.

Anahtar Kelimeler: Şarj istasyonu, enerji yönetim sistemi, mikroşebeke, fotovoltaik sistem, süperkapasitör.

ABSTRACT

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Recently, the increased penetration of renewable sources, the growing of the load in terms of electric vehicle (EV) as well as other electrical loads and the power electronics' advancements make the power networks in their current shape incapable to adapt these changes. Thus, new techniques in addition to energy management methods should be applied in order to convoy the recent technologies and changes in both load and source sides. In this study, an energy management system (EMS) is designed for a residential based microgrid that consists of two parts. One of them is a residential compound that comprises a photovoltaic system (PV) and battery storage system (BSS). The second is a charging station compound comprising a photovoltaic system and a super-capacitor energy storage (SCES). During peak hours, the usage of super-capacitor (SC) provides the load shifting in terms of charging of EVs. An optimization algorithm is applied for the proposed EMS so that both the SCES and BSS avoid charging in the peak period. Optimal energy consumption will be obtained according to different scenarios of operation. Thus, an increase in energy efficiency is expected to be. Furthermore, the grid will avoid an extra overload in peak time.

Keywords: Charging station, energy management system, microgrid, photovoltaic system, super-capacitor.

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ABBREVIATIONS

BSS	:	Battery Storage System
DOD	:	Depth of Discharge
EMS	:	Energy Management System
ESS	:	Energy Storage System
EV	:	Electric Vehicle
FC	:	Fuel Cell
HES	:	Hybrid Energy Storage
MG	:	Microgrid
MT	:	Micro Turbine
PV	:	Photovoltaic
SC	:	Super-Capacitor
SCES	:	Super-Capacitor Energy Storage
SMES	:	Super Magnetic Energy Storage
SOC	:	State of Charge
WT	:	Wind Turbine

SYMBOLS

Capacitor’s Capacitance	:	C
Capacitor’s voltage	:	V
Charges in capacitor’s plates	:	Q
Charging state of the residential battery	:	$E_{BATTERY}$
Charging state of the Super-Capacitor	:	E_{SC}
Dielectric constant of the dielectric material	:	ε_0
Gurobi variables	:	F1, F2, Z1, Z2, E_{GRID1}, E_{GRID2}, Y, G
Hourly coming energy from the residential PV	:	E_{RE}
Hourly coming energy from the station PV	:	E_{RES}
Hourly EV load on the station	:	E_{ev}
Hourly energy taken from the extra station PV energy	:	E_{extrta}
Hourly residential load	:	E_{DEMAND}
The distance between capacitor’s plates	:	d
The electrode surface area	:	A

1. INTRODUCTION

Electricity is a must everywhere in this world. Therefore, delivering electrical energy efficiently is an important issue since electricity was founded. Increasing energy efficiency not only saves money but helps in saving the available energy from the risk of energy price fluctuations and supply shortages. Although many efforts have been made to increase efficiency over time, it is still a tough mission because a lot of things are changing in the power grid in terms of transmission process, generation, loading, power equipment, switches, and storage technologies. Even the arrangements in the grid are changing. Thus, contemporary solutions and strategies should be found to deal with these updates on the power grid.

The first electricity transmission process made with direct current (National Energy Education Development Project 2005), but that model was poor comparing with AC mode which was proposed later on by Nikola Tesla. Such as the limitations in case of stepping DC voltage up and down. Furthermore, the system itself was also more expensive because it used thicker and heavier shielded distribution wires to minimize current loss as well as forcing DC electrical generating plants to be near the loads. Thus, on one hand the direct current has lower losses than AC. On the other hand, it was unreasonable to discuss or improve DC options for the power network for many decades.

Later on, many things have changed on both generation and load sides, illustrated by renewable energy appearance as a power source becoming more important progressively (Usher 2019). In the case that a PV cell is connected to the grid, it provides DC different than AC in the grid. Similarly, on the load side, some of DC alternatives have started to appear such as reluctance motor, permanent magnet DC motors with high magnetic intensity materials, and EV load which considers one of the most defying issues in the near future (Joao Vitor Fernandes Serra 2018). Because vehicles used to have their own source of fuel, but now they are overloading the power grid. Although EVs are very important to the future due to being ecofriendly, they should be entered into the grid in a well-organized way to avoid overloading problems. Thus, the changes in both load and source sides make the efficient use of power more challenging and increase the necessity of energy management.

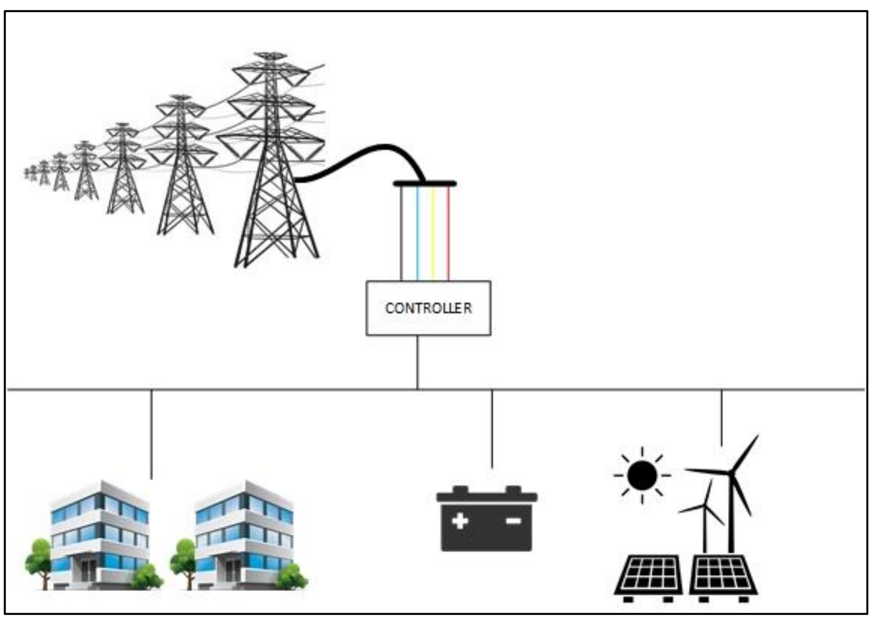
Besides these changes, the power and protection devices have been developing as well. For example, nowadays, some of the relays have a digital interference (Ghorbani et al. 2019), making them more controllable. Above all, the most important advancements are those in power electronics. It does not change the way of transmitting electricity only, and they made a revolution over mechanical devices in all domains. Because the semiconductor switches have high frequencies with negligible power losses (Makonin 2020). Furthermore, they made the grid more controllable. For example, now to create three-phase currents from single phase one, converting AC to DC then making a three-phase set of currents through PWM considers the most suitable solution in terms of costs and power quality. In other terms, the power grid now consists of AC and DC elements as well as inverting techniques between them which facilitates the combination between them.

Along with AC/DC issue, storage technologies also have been changed a lot in order to follow up the changes in the other network's elements. Recollecting power transmission history, storing electrical power had no vital role for a while. The storage was being needed only in case of backup systems, or MG in rural areas (Nikos Chatzēargyriu 2014). That is why research scopes did not focus that much on improving those kinds of technologies. However, present-day society requires a secure energy feed. Along with the growing of energy demands worldwide, developing the infrastructure reliability, security, and quality is such a challenging issue that needs enormous investments (Ghorbani et al. 2019). According to the International Energy Agency, global investments required in the energy sector over (2003–2030) are approximated to £ 13.53 trillion.

Gradually, most of the grid elements become active elements. which means that they have the ability to be controlled. Furthermore, miscellaneous microgeneration technologies like micro-turbines (MT), photovoltaics (PV), fuel cells (FC) and wind turbines (WT) are connected to the LV side, which needed to be controlled as well. Therefore, incorporating innovative solutions for the grid's architecture s is a considerable step towards merging the power network with the most recent updates in the grid elements.

Thus, a new concept in the grid structuring appeared as the name of microgrid. Which is defined according to the EU research projects (Hatziargyriou et al. 2006; Schwaegerl et al. 2009) as a small scale grid that is composed of Low Voltage distribution systems together with distributed energy resources, storage devices (such as SCES, flywheels, and batteries) and flexible loads. These systems can be operated in a non-autonomous or autonomous way depending on their interconnection situation to the main grid. The operation of micro sources in the network can give huge benefits to the overall system performance, in the case that they are managed properly. In other words, Microgrid is an integration platform for supply, storage units, and demand resources located in a local distribution grid. Furthermore, it should have the ability to handle both grid-connected and islanded state operations. The Figure 1.1 describes microgrid concept much clearly.

Figure 1.1:Microgrid main scheme



Not only the technologies are updating, but the type of grid itself is changing too. Because the normal power grid has disadvantages. Although it has a huge capacity with a lot of generators and other sources, if a part of the grid is damaged and should be repaired, everyone on the grid is affected. Consequently, the concept of microgrid has been started to be applied as an alternative distribution system. Microgrid is essentially a local grid with independent control capability, which means that it can disconnect or ''island'' from the main traditional grid (Hatziargyriou et al. 2006). Then operate autonomously by using local energy generation such as generators, batteries, renewable sources…. In other words, it is a smaller version of a traditional power grid. The microgrid solution has many advantages not only that it provides more flexibility to the grid since it can operate in island mode. But also it increases the power reliability due to the closer proximity between the power generation and consumption. Moreover, it is eco-friendly because it can integrate with renewable energy sources.

To sum up, increasing the efficiency of the electric power grid is a major issue since electricity is a must for everyone. However, many options may be applied even DC or AC or a hybrid system depending on the available loads and sources. In addition to this, electric vehicles are increasing gradually which means extra overloading on the grid. Furthermore, new technologies have been started to materialize like novel protection devices and energy storage technologies. In like manner, the construction of the grid is also developing and the microgrid is one of the solutions that solved some of the problems in the typical power grid. Thus, from all these updates new designs can be created to increase power efficiency. Consequently, in this study an energy management approach is tested on a residential compound consists of 8 residential units and they consider as a load. Moreover, it comprises solar PV array with a bank of batteries. Furthermore, this MG contains a fast charging EV station. And the EV loading will be handled by a bank of super-capacitors which feeds EV batteries that are below 50 percent until it reaches this limit. On the other hand, if any connected EV has an extra charge (above 50 percent). It gives this portion to the grid. However, the SCES charges from has its own PV array. And this MG is an on-grid system.

Since the electricity price differs by different day times, the SC bank as well as the BSS will be charged in a certain schedule in order to avoid peak time prices. This also rescues the grid from any overload may be created by EVs. This EMS considers many scenarios so that the effects of changing an element in the system can be noticed clearly.

2. LITERATURE REVIEW

Microgrid-related topics are a relatively novel horizon of research. At the same time, they consider one of the most important research scopes currently. Many studies have been made covered variant aspects from the microgrid. According to Ahshan,et al.(2010), it proposes the simulation of a microgrid system based on wind and hydropower sources and addresses issues related to the system's operation, control, and stability. It consists of a small hydro generation unit and a wind farm containing nine induction generator wind turbines with variable speed and double-fed features. The grid works in three modes of operations. The technical challenges for the microgrid system under investigation can be classified, firstly the grid-connected system, the secondly isolated system with wind power generation, and finally, the isolated system without wind power generation. As a result, the simulation indicates that dump load and suitable storage system along with proper control scheme are also required for the operation of the study system in a microgrid scheme.

Then, to clarify the different types of microgrids, the study by Zhu and Zhang (2014) shows the advantages and application of these three types of microgrids. Furthermore, the grid framework, energy management, operation control and protection strategy of AC-DC hybrid microgrid are well summarized. AC microgrid is a comparatively fully developed technology and has applied to power system. Compared to AC microgrid, DC microgrid has some advantages in enhancing power quality, reducing energy consumption and other cost. AC-DC hybrid microgrid integrates the advantages of AC and DC microgrid, which can decrease AC and DC or DC/AC conversion equipment.

Besides the grid types, storage techniques should be taken into consideration since it is a focal segment of the MG for many reasons. First, energy storage devices exist in almost every MG, because every renewable energy source needs a storage technique to cover up the load in case of shortage or absence of the natural resource of energy. Which considers the most common usage of energy storage. In this case, the efficiency of the storage system is really important because its size may reach hundreds of megawatts, while the losses in a cable or leakage on the load side, conversely, have less significance. As an illustration, Qiang et al. (2017) is getting the lithium battery cell as the research target through combing the equivalent circuit method with the 2nd order RC equivalent circuit model which is based on dynamic impedance is formed. The parameter values of voltage source, resistant and capacity differ with the change of State of Charge (SOC). Accordingly, when SOC is within (20-100) percent range, the parameter value of impedances tends to be stable. At last, the paper makes use of MATLAB to do the simulations of charging experiment of the model, balances the differences between the simulation outcomes with the experimental result and concludes the relative error between the external feature of model voltage and the measure data from the experiment, which is within 4 percent.

In like fashion, two energy storage techniques may be used as a Hybrid Energy Storage (HES) so that the advantages of different technologies are taken in particular, Mouratidis et al. (2019) discusses a hybrid energy storage system involves a flywheel and a lithium-ion battery. As the losses in the battery increases by the increasing of the number of cycles, the aim of inserting flywheel storage to the system is to decrease battery cycles since the cycling is not an issue in the flywheel. At the same time battery still important in the system due to low energy density in the flywheel. Thus, this combination has made up and tested by a simulation for one day so that primary control reserve is analyzed. Moreover, a four-year simulation which enables the estimation of the battery aging over time has been tested. Which reveals an improved battery lifetime.

Energy storage techniques are not only a backup for the source, but their usage may be multifunctional. For instance, energy storage technologies may be used to fed the network by reactive power to stabilize the voltage levels. Raha et al. (2016) proposes a hybrid Capacitor-Super Magnetic Energy Storage (SMES) based var compensation is made use of to solve the reactive power dispatch for the non-restructured and restructured network. In the final analysis, the hybrid capacitor-SMESs achieved 3.93 percent more power loss reduction and 1.53 times improved economics compared to single. Furthermore, the hybrid capacitor-SMESs gained 0.23 percent upgraded global welfare from the study having no var compensators.

Since flywheel energy storage is not the only technique that can be used, it is necessary to go through all of them so that the best decision can be taken to acquire better simulation results in any research. Mamen and Supatti (2017) shows a survey of miscellaneous HES systems applied for RE sources. The structure of HES systems is comparatively studied. Capital cost, power rating, and characteristic of storage devices result in an optimum combination of SMES with battery and SC with battery are all evaluated. It is concluded that the mixture of the SMES with battery is appropriate for the power generation system with high power penetration, like wind power generation. Nevertheless, the combination of SC with battery fits the lower power penetration system like a PV generation system.

As the grid's function is to deliver the energy from generation to the load side, increasing this procedure's efficiency should be a main target for the research. In fact, there are many ways to increase the efficiency of the grid. Optimization may be the most common method to do that job by choosing some grid parameters to maximize or minimize them in order to get the optimal value under some constrains. For instance, Meng et al. (2015) proposes a model for computing the optimal size of a grid connected DC micro-rid. Taking into account the dissimilarities between DC and general AC microgrid and the operating mode of the DC microgrid system with hybrid energy storage system, the sum of all costs of distributed generations are set as the optimal target. The optimum solution for sizing association of DC microgrid with hybrid energy storage system is prevailed and compared with single battery storage, then as a result, it is verified that the better performance is the performance of hybrid energy storage.

Likewise, an optimization for network operation schedule can also be applied. Seyyedeh Barhagh et al. (2020) shows residential compounds combine photovoltaic system, and electric vehicles. The operators of the compound can apply demand response programs in order to decrease their operating costs with satisfying energy demands at the same time. The existing EVs can share the system in supplying energy demands which provides economic benefits. Moreover, the optimization process is modeled as mixed-integer linear programming as well as general algebraic modeling system to get simulations in different 10 scenarios, then the results are presented for comparison. The proposed models for energy units in the system were determined and the optimal system's economic operation was found as well. Additionally, power generated by the PV unit was efficiently used to supply energy demand and charge the EV. Later, the stored energy was released to be either exported or used for supplying the demand. In addition, according to the power prices, within the periods with lower prices, the upstream grid power was imported to help the system fulfil energy demands. As a result, the total expected cost of the system is reduced up to 37.31percent. Furthermore, it should be illustrated that different scenarios were generated to model stochastic driving patterns at the arrival time of the electric vehicles as well as the obtained revenue from exporting excess power generated by the PV unit can also afford economic benefits for the system.

Optimization is not the only way for making energy management, but also it can be done using a certain control or algorithm. For example, Cetinbas, et al. (2019) discusses a small-scale ACMG with PV as an energy source, a plug-in EV, and a residential load shifting control. Many different scenarios are applied on this grid to manage power consumption and supplement, by switching on/off some loads and sources in certain times. The results show significant savings in the bills, ranging from 32.11 percent to 71.23 percent. Furthermore, the payback period can be reduced to the durations that change between (6 – 14) years.

Analogous to the previous study, Tran et al. (2019) proposes efficient energy management approach for the home photovoltaic systems to feed the electric vehicle battery charging facility while utilizing the electrical vehicle battery as an energy storage system that can alleviate the home photovoltaic impacts and permit the development of home photovoltaic systems in power grids. Thus, the system controls the power balance between the home photovoltaic source, electrical vehicle battery energy, the home load, and the grid demands victoriously.

In a like manner, Guddanti and Illindala (2019) represents cost saving optimization model for a DC microgrid, proposes a load is patch model for energy management system in a DC microgrid is made up of solar, wind power, diesel generator, and battery energy storage system. Depending on the forecasted data and real time price of electricity, the system needs to allot the power supplied from the distributed energy sources and grid to meet the load demand at optimum cost. The system has two modes of operation; in the first one the power generated from renewable sources meets the demand. Whether in the mode 2 an optimization model is solved. The energy management system with proposed model gave remarkable cost savings for the microgrid owner.

As the goal of this study is to create a load shifting EMS, Ul Haq et al. (2013) shows an optimum operating situation which is recognized by comparing diverse Energy storage technologies. The advantages from a system like this are not only ensuring the on-time fast charging but it also benefits in reducing the load in the peak-time. As a result, charging station based on SC energy storage system may be a reliable option with uninterruptible power supply to recharge electric vehicles.

After all, it is obvious that not all previous researches focus on all aspects in the grid. Some of them like Ahshan,et al.(2010), Zhu and Zhang (2014), Qiang et al. (2017), Mouratidis et al. (2019), Raha et al. (2016), Mamen and Supatti (2017) and Ul Haq et al. (2013) define different types of the microgrids or storage technologies. By comparing between their characteristic or by simulating them to exhibit their usage and advantages. In other words, they represent different grid elements. However, there are a lot of researches do not focus attention on comparing between different grid and storage types but they would rather manage the energy usage in the grid by optimizing the optimal size of some element or optimal schedule such as Meng et al. (2015), Seyyedeh Barhagh et al. (2020), and Guddanti and Illindala (2019). Or by trying their own pre-determined scenario or control strategy like Cetinbas, et al. (2019) and Tran et al. (2019).

In fact, this study has some common points with previous mentioned studies. For example, it relays on different power prices like Cetinbas, et al. (2019), but this study does not cut off any load. Furthermore, this study benefits from super-capacitor technology to avoid charging EVs in the peak time. And it applies optimization similar to the study of Guddanti and Illindala (2019), but this study discusses EV entering to the grid as well as inserting the super-capacitor technology. In a like manner it differs from Meng et al. (2015), Seyyedeh Barhagh et al. (2020), and Guddanti and Illindala (2019) because this study combines between optimizing minimum operating cost and considering different power prices by the day times with the help of super-capacitor technology. Ul Haq et al. (2013) is the closest study to this study because it talks about using SC for load shifting. But the difference is that Ul Haq et al. (2013) shows the electrical behavior of different systems. Whereas this study shows how much power and price can a system like this save by applying an hourly power simulation. Furthermore, this system manages even the residential load. In brief, it applies a certain algorithm related to different loading-periods, then the minimum operational cost in each cycle of this algorithm is calculated. Taking the SCES as a base for new EV charging station.

2.1 OBJECTIVE of THE THESIS

In this study, an EMS is proposed and applied on a MG. The main problems that are caused by the EV connection are:

A. EV battery overloads the power cable of the home due to their extremely high power rating in comparison with the power that the home appliances absorb. Especially when they charge in fast charging mode. Furthermore, this huge load most probably connects in the evening to the grid. Therefore, this share in the average evening peak demand could rise up to 10 percent without any management scenario in the core EV markets like China, European Union, and the United States (IEA 2020)

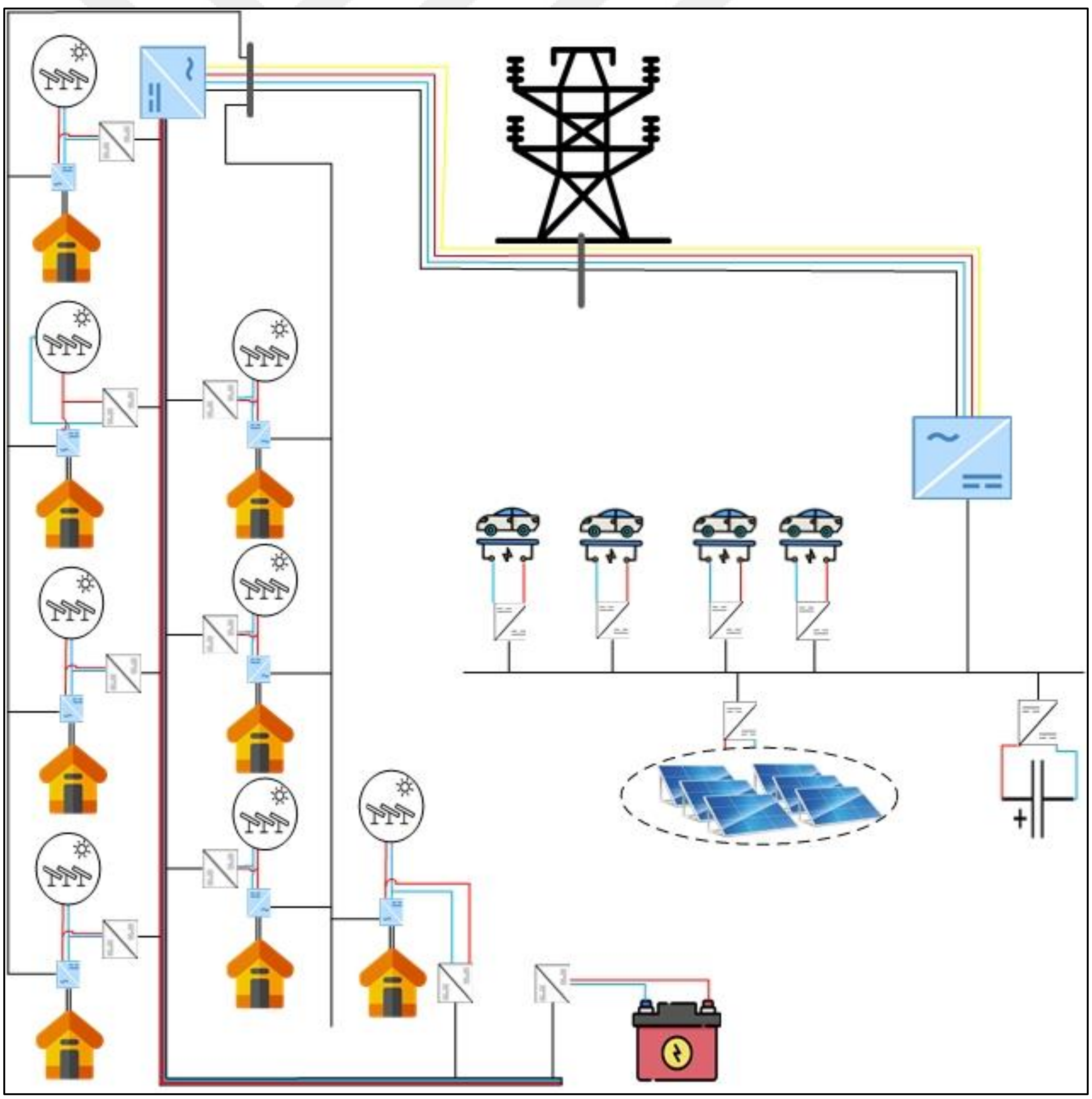
B. EV batteries connect to the grid at the reaching time of the vehicle. Which is generally at the peak price period. Which makes the charging process such an overpriced as it is a long-term, daily issue for EV owners.

Therefore, an energy management strategy will be discussed in detail in order to avoid previous mentioned problems. This strategy is applied on a MG consists of residential load, a SC based EV fast charging station. And PV arrays on the top the residential houses with a BSS as a back-up for the array. In a like manner, PV array exists on the top of the station. The main objective of the EMS is to decrease the loading on the grid during the peak hour due to high prices at that time as well as the high load that is already existed. Therefore, in the residential part of the grid the battery is not allowed to charge during peak hours. In a similar way, the charging station has a SCES to shift the EV load from the peak hours. In detail, when a certain EV connects to the station. The system checks its SOC. If it is higher than 50%, the EV battery gives the grid the above 50% portion of power. On the other hand, if the SOC is lower than 50%, the EV battery charges from SCES until reaches 50% SOC. After the ending of peak hours, the remaining portion of each connected EV in the peak hour charges from the grid. At that time the loading on the grid is decreased in addition to the lower charging price. Therefore, some benefits for this MG are expected to appear in the simulations by using the proposed EMS.

3. COMPONENTS of THE MICROGRID SYSTEM

In this chapter, all the components that constitute this system are going to be discussed in detail. This system is mainly made up of a residential microgrid which consists of a residential compound and a charging station. Each of them has a renewable based generation system and an energy storage system.

Figure 3.1: The proposed a residential microgrid system



The Figure 3.1 shows the structure of the EMS. The left hand side of the diagram is the MG before creating the fast charging station. All the PV arrays are connected to each other so that the maximum benefit can be taken from all arrays. Furthermore, the system has a central battery bank which decreases the cost in comparison with a battery in each unit. In the right hand side, the diagram of charging station is placed. In particular, in the residential side every customer has 3 possibilities for taking the needed energy. Even from PV panels during the daytime, or from the battery in case the PV power is not enough for the load or in evening/night times, or from the grid when the other sources cannot give the load fully or partially. The solar is connected to the grid. Therefore, it is on-grid MG system.

On the other side of the diagram, the charging station contains its own PV array because the existing PV panels are designed to fit the residential demand and they do not have sufficient capacity to cover up a considerable part of the EV load. Thus, the EMS manages both the residential load and the charging station in the same way. It does not give permission for charging during peak price hours. BSS can charge either from the grid or PV arrays. But SCES can charge only from PV.

The charging station gives the residential side the extra power from the PV when the SCES is full. The sizing and specifications were discussed in detail in section 3.1. and Section 3.4 as well for both BSS and SCES.

3.1 THE RESIDENTIAL PART of MICROGRID SYSTEM

The residential part of the MG system consists of eight residential houses. Each house is a luxury duplex house as well as it has a PV system on its roof. Moreover, centralized battery energy storage system is designed to use for all residential customers. The storage system is consisting of Lithium-ion battery cells.

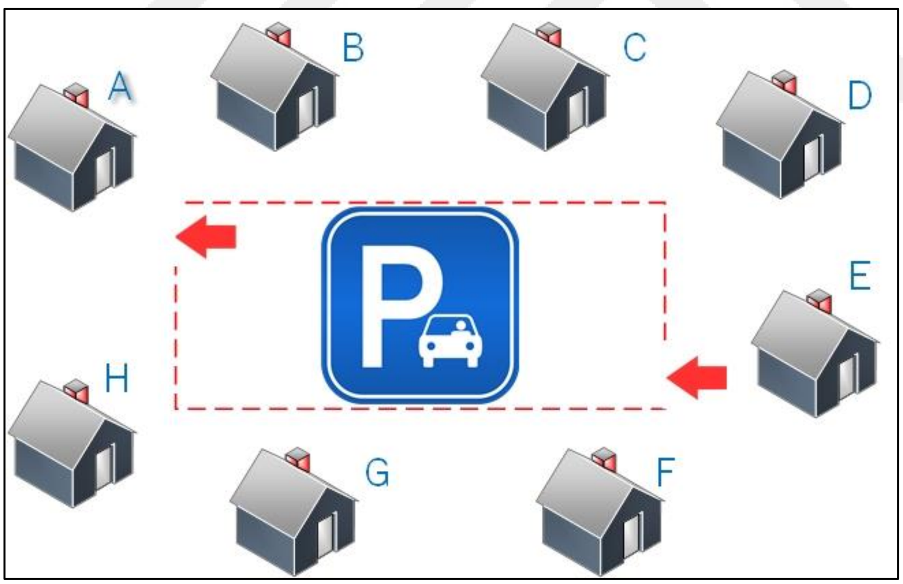
The consumption profile of residential houses is given in Table 3.2. This given data were taken from Makonin (2020).

Table 3.1: Residential load profile summary

Residential Unit	Daily Average Consumption (kWh)	Yearly Consumption(kWh)	Peak Consumption (kW)
A	8.243	3008.68	4.14
B	22.344	8155.66	5.00
C	16.197	5911.82	6.37
D	15.915	5808.92	4.53
E	14.522	5300.62	5.02
F	12.723	4643.82	5.31
G	23.210	8471.48	6.37
H	37.138	13555.52	7.16

Source: Makonin (2020)

Figure 3.2: Residential compound main scheme



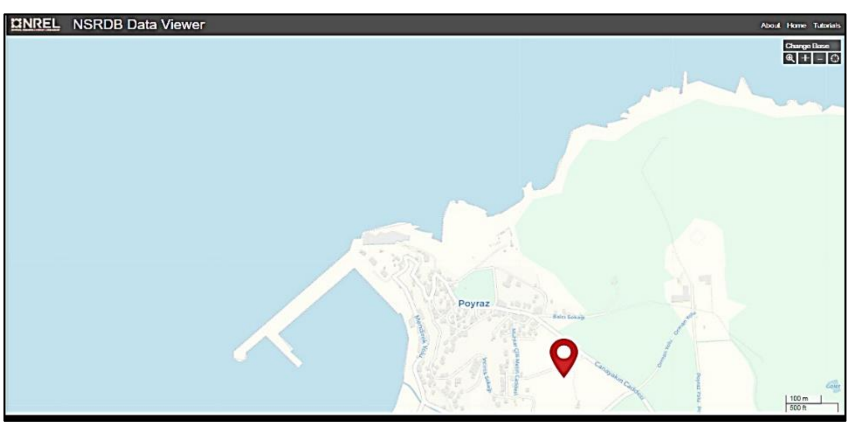
3.1.1 PV Design

By considering the residential consumption profile, the PV system was designed on the given system. In addition to this, some extra capacity takes place taking the advantage of large spaces on each roof($250m^2$each one). Furthermore, all the PV panels in all residental units will be connected together in order to cover the demand properly.

The previous system's specification is tested through System Advisor Model (SAM), which has models for grid-connected photovoltaic systems that consist of a photovoltaic array and inverter. Then it is able to run models hourly or sub-hourly simulations to calculate the power system's electrical output. The sum of these values is the total annual outputs. In addition to this, SAM considers all the types of losses that may face any real pv system as well as it has got a real time weather data which is measured through all over the world. The calculation process is done with number of steps. To understand them, the unit-A is taken as an example:

a. Firstly, the location should be detected so that SAM can consider a realistic wheather conditions. Then do the simlation according to them. The Figure 3.3 shows the selected location in Istanbul.

Figure 3.3: Location of the residential compound



source: Mouratidis et al. 2018

According to National Renewable Energy Labratory(NREL), the percentage of total rooftop area suitable for PV in residental usage is around 27percent. Therefore, the maximum avaiable area in this case study is 67.5 m^2. And the maximum array capacity is around 10 kW DC.

b. From the load profile table, the peak load of unit A is 4.14 kW. Taking into consideration some extra capacity, array capacity will be selected as 6 kW DC.

$$inverter\ size = \frac{array\ capacity}{\frac{DC}{AC} ratio} = \frac{6}{1.2} = 5\ \ kW\ AC \tag{3.1}$$

c. DC/AC ratio depends on the inverter. Beore choosing an inverter, an assumption of 1.2 (standard) can be placed.

d. After choosing the inverter, some information from its datasheet is needed: min. MPPT voltage = 200 V, max. MPPT voltage = 480 V

e. Select a cerrtain module : Trina solar TSM-250PA05A.18, then from the module dataheet Vo.c = 37.8 V and module size is 250.1 kW.

f. Calculate the number of arrays:

$$Number\ of\ modules = \frac{arraay\ capacity}{module\ size} = \frac{6\ KW}{250.1W} \sim 24\ module \tag{3.2}$$

g. Calculate the maximum and minimum number of modules/ string so that the modules can be distributed on strings correctly

$$max.modules/string = \frac{\text{max.MPPT volt}}{\text{Vo.c}} = \frac{480}{37.8} \sim 12 \quad \textbf{(3.3)}$$

$$min.modules/string = \frac{\text{min.MPPT volt}}{\text{Vo.c}} = \frac{200}{37.8} \sim 6 \quad \textbf{(3.4)}$$

h. Choose the array size that is suitble to the defined limits : 8*3

In like manner, the other residential units can be calculated. Table 3.2 shows the results of calculations of all customers.

Table 3.2: PV sizing for residential part.

Residential Customer	Array Capacity (kW)	Inverter Size (kW)	Number of Modules	Module Open Circuit Voltage (Voc) (Volt)	Module Maximum Power (W)	Array Size (Module × String)
A	6 DC	5 AC	24	37.8	250	8 × 3
B	8 DC	6.73 AC	32	37.8	250	8 × 4
C	10 DC	8.36 AC	40	37.8	250	10 × 4
D	8 DC	6.73 AC	32	37.8	250	8 × 4
E	8 DC	6.73 AC	32	37.8	250	8 × 4
F	8 DC	6.73 AC	32	37.8	250	8 × 4
G	10 DC	8.36 AC	40	37.8	250	10 × 4
H	10 DC	8.36 AC	40	37.8	250	10 × 4

source: Mouratidis et al. 2018

3.1.2 Battery Selection and Sizing

Batteries consider as an essential part of the MG. Because it covers up the fluctuations of the renewable energy resources such as solar energy. Therefore, battery selection is important for the whole energy system.

The selection process depends on the type and size of the battery. Any variation in each of them makes changes in the price too. In fact, this process is fully dictated by the load as well as the customer. For example, if the battery system is only responsible for feeding the lights of the home or a part of the load, then the quality of the system is no more a priority. On the other hand, if it deals with sensitive loads or the number of cycles is relatively high so that the cycling efficiency can enormously affect the cost, high-quality batteries give extra benefit and may be a must in some cases (Dell,et al. 2001).

3.1.2.1 Battery type selection

Typically, two main technologies are used in residential PV systems. They are lithium-ion or lead acid. Both technologies have advantages and disadvantages. Table 3.3 shows the main differences between them.

Table 3.3: Comparison between lead-acid and lithium-ion batteries

Battery Type	Cost/Cycle ($)	Charging time (hour)	Cycle Life	Maintenance	Safety
Lead-Acid	0.1	8-16	500 – 1000	3 to 6 months	Thermal runaway may occur with improper charging
Lithium-ion	0.14	2-4	1000 – 10000+	not req.	safe

source: Buchmann 2017

In this case, a Lithium-ion battery is a suitable option for many reasons. First, the number of charging and discharging cycles is relatively huge because the battery covers fully 8 residential houses. Thus, cycling efficiency is a really important issue. Then, since all the houses belong to the same compound, making a central battery unit is an applicable option. Therefore, the extra money can be saved in comparison with making a separate unit for each home. Additionally, Lead-acid batteries require more maintenance as well as they are less safe than Lithium-ion batteries. In other words, a Lithium-ion battery is a better option for this case.

3.1.2.2 Battery sizing

The next step is calculating the capacity of the battery bank dependig on our daily kWh. The battery bank capacity can be expressed by the following equation:

$$\text{Battery Bank Capacity} = \frac{daily\ kwh \times Number\ of\ Days}{D.O.D} \quad \textbf{(3.5)}$$

a. Depth of Discharge (DOD) can reach up to 70 percent in order to save the battery and benefit from it as much as it can be possible.

b. Since the battery is going to work only in the peak and mid-peak times, the operating hours are 16 hours. Then the capacity is multiplied by a ratio $\frac{16}{24}$.

c. Concerning to daily kWh, there are a lot of options can be considered. Because there are many factors can be considered such as the available budget and the growth of the load. However, in this study many scenarios will be tested. In these scenarios, different battery capacities will be tested as well. Therefore, two scenarios are existed. One of them considers the average daily load. The other considers the maximum daily load. Thus:

$$\text{Battery Bank Capacity\_1} = \frac{275 \times {}^{16}/_{24}}{70\%} = 262 \text{ kWh} \quad \textbf{(3.6)}$$

$$\text{Battery Bank Capacity\_2} = \frac{150 \times {}^{16}/_{24}}{70\%} = 145 \text{ kWh} \quad \textbf{(3.7)}$$

3.2 CHARGING STATION PART of MICROGRID SYSTEM

EV technologies have become one of the most salient research scopes recently. Because it is related to a wide social group since everybody has a car nowadays. Furthermore, there are many aspects that can be studied in this field. For instance, the effects of EVs on the network, types of charging, charging duration, vehicle efficiency. All of these examples also differ from country to country and from research to research depending on different

EV users over the world as well as different research methods and techniques. In other words, EV-related topics are the future due to being everyone's need.

After setting out the problems that may be occurred due to the connection of EVs to the power grid. Alternatives for a solution should be selected. Since the problem is overloading the MG as well as charging EV batteries at the peak hours, then another element should be added to the grid so that EV batteries may be shifted to another time taking into consideration the grid limits. For load shifting, Energy Storage System (ESS) is the most suitable choice for these reasons:

A. Since ESS contains energy, it can charge EV anytime starting from the connection time. Whereas other shifting solutions need to charge according to a schedule. And the scheduling alone without a back-up creates many problems for users. Especially when the EV batteries are on the lower levels or empty.
B. The probability of benefitting from a PV array is low in the absence of ESS. Since most of EVs connect in the evening.
Afterward, a proper selection between many techniques should be made. Consequently, the Table 3.4 sums up the most well-applied ESS technologies (Mamen and Supatti 2017).

Table 3.4: Specifications of most common ES technologies

CHARACTERISTICS	SC	SMES	LEAD-ACID	LI-ION	FLY-WHEEL
LIFETIME(YEAR)	20+	20+	5-15	5-16	15
CYCLES	100000+	100000+	500-1000	1000-10000+	20000+
CYCLING EFFICIENCY	98%	90%	80%	80-95%	90%
POWER RATING	0-300KW	100KW-10MW	0-20MW	0-100KW	0-20MW
CAPITAL COST/kWh($)	300-2000	10000	200-400	600-2500	10000

Source: (Mamen and Supatti 2017)

Firstly, the priority of desired features should be pointed out. Most new EVs charge in fast charging mode. A fast-charging station will be the option for the installation. Therefore, a fast-response technique is needed. In addition to this, efficiency is important also as well as the battery life, because ESS will handle such a huge power therefore bigger cycling losses. Thus, The Super Capacitor Energy storage technique is the best option for these reasons:

a) It has a really high number of cycles and lifetime.

b) The cycling efficiency of SCES can reach to 98percent.

c) It considers a reliable power source for situations like this.

d) The range of required power is compatible with its range of usage.

e) Since the probability of getting a car connected through the daytime is low, the absorbed power may reach high power limits. This is a big advantage for SC because they can be fully charged and discharged in few seconds. On the other hand, the other techniques are limited with lower charging rates.

3.2.1 EV Load

EV chargers also developed over time. They started as normal AC load that can be connected to a power socket in the home. Then other levels of EV chargers were developed. Based on the power rating, EV chargers can be divided into Level 1, level 2, and Level 3. Table 3.5 summarizes the characteristics of the three different power levels.

Table 3.5: EV charger's levels

Power Level	Charger's Power Rate (kW)	Charging Time
level 1	1.4	20 h
level 2	7.2	5-6 h
level 3	50-350	15-30 m

source: Levy et al. 2020

This study handles the charging level 3 which is considered a prime issue because:

a) Fast charging is targeted to be used widely in the next generations of EVs. Whereas the other types of chargers are already used a lot worldwide. Therefore, they are no longer an issue for new researches.

b) The normal types of EV chargers do not consider an abnormal load since they take many hours for charging. On the other hand, fast charging EVs absorb many KWs from the grid in less than one hour.

Load determination is the base of any designing process. With this in mind, EV load analysis will be done in this section. This procedure depends on many factors. First, EV batteries have different capacities starting from 17.6 up to 100 kWh (Giordano et al. 2019). Additionally, there are many types of vehicle drivers. But they can be divided into three main categories: daily worker, shift worker, and freelance. The main difference between them is the job type or the lifestyle. According to the working hour systems in Turkey, Table 3.6 shows the reaching time of these categories.

Table 3.6: Types of EV users

Category of the User	Expected Arriving Time to The Station
Daily-worker	(17:00-22:00)
Shift-worker	(6:00-9:00)
Freelance	randomly

source: Giordano et al. 2019

Not only the user's category can impact the EV profile. But the type of vehicle in addition to the battery capacity has an impact on the load profile. In this study, level 3 charging is taken into account. In fact, not all EVs have Fast charging abilities. Consequently, Table 3.7 shows the number of EVs that can charge on the fast charging mode.

Table 3.7: EV Brands of level 3 charging

Brand	Model	Max. Charge Rate
VW	e-golf	40
BMW	i3	50
Chevrolet	Bolt	56
Chevrolet	Spark	56
Hyundai	Kona	74
Hyundai	Ioniq	74
Kia	Niro	74
Kia	Soul	80
Nissan	Leaf Plus	100
Jaguar	Ipace	105
Audi	e-tron	153
Tesla	model s	181
Tesla	model x	181
Porsche	Taycan	225
Tesla	model 3	250

source: Guddanti and Illindala 2020

Accordingly, an EV load profile can be created. For this residential compound four fast-charging EVs is a reasonable number. Because this type of EV cannot be afforded easily due to its high price. Furthermore, not all people prefer this type of EV or even the EV choice itself.

Afterward, three cars are chosen from the table above so that the load profile can be a little bit diverse. Which they are: Hyundai Ioniq, VW e-Golf, and BMW i3the required characteristics are taken from their datasheets in order to model them accurately. Subsequently, daily reaching times and DOD are created according to the defined limits in the datasheets and users' categories. as a result, hourly EV load profile is created.

Table 3.8: Charging station's user profile

USER	EV TYPE	EV USER CATEGO
1	Hyundai Ioniq	Daily-worker
2	Hyundai Ioniq	Daily-worker
3	VW e-Golf	Daily-worker
4	BMW i3	Daily-worker

Table 3.9: EV's batteries specifications

EV TYPE	BATTERY CAPACITY (kWh)	ENERGY CONSUMPTION (kWh/100km)	REQUIRED TIME(FROM 0 to 80%) in minutes
Hyundai Ioniq	34	18.7	24
VW e-Golf	32	20	41
BMW i3	38	13.1	34

3.2.2 Parking Area Design

The car parking's area should be determined in an engineering way so that it meets the real with the other calculations such as the PV calculation. For this purpose, the standards in Design recommendations for multi-storey and underground car parks are going to be applied (Institution of Structural Engineers 2002). Consequently:

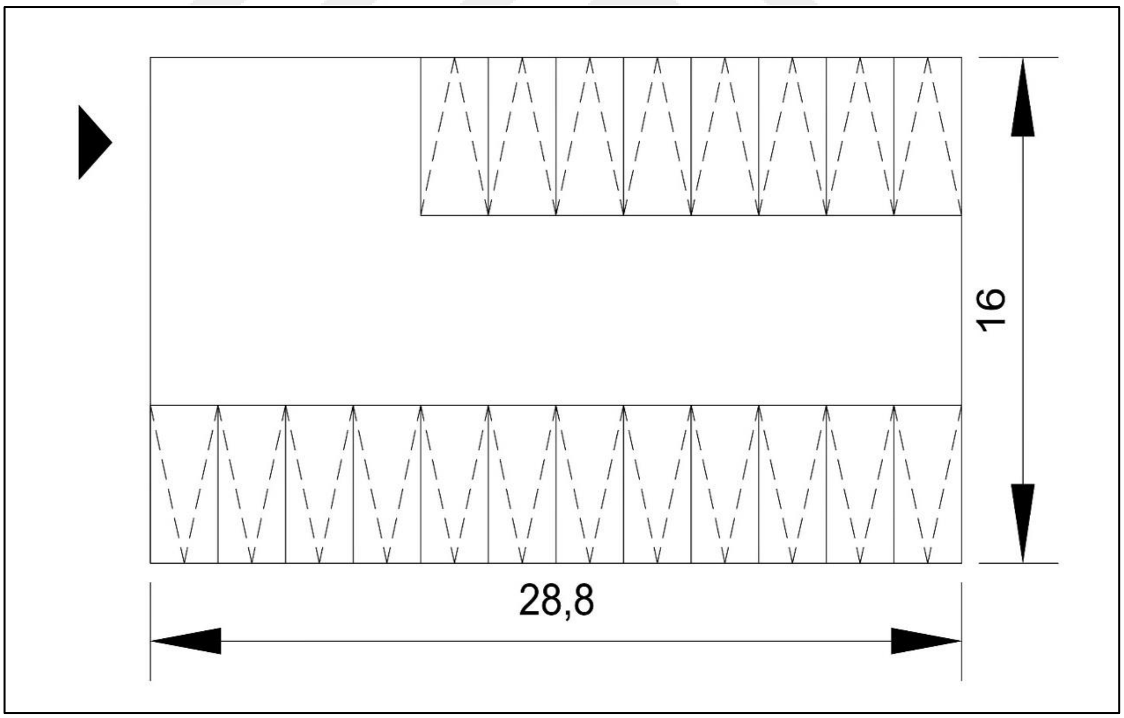
a. Each residential has two parks.

b. 4 additional parks exist for guests.

c. The dimensions of each car park is (5m*2.4m).

d. From the plan (Figure 3.4**)**, the total parking area is 316.8 m^2.

Figure 3.4: The layout of the parking area



3.2.3 PV Design

In section 3.1.1, the percentage of total rooftop area suitable for PV was 27 percent. Because it is designed for a residential load. Here the array is for a charging station. Which means there is no limitation like this. At the same time, the array size should fit the load size so that the oversized array does not increase the initial cost. Therefore, the total module area is going to be 200 m^2(around 65percent of the rooftop). The sizing method is the same as it was in the section 3.1.1. Also SAM is used for the modeling. And the results are sown ay the Table 3.9.

Table 3.10: The sizing and speciation of the charging station PV array

ARRAY CAPACITY (kW)	30
INVERTER (kW)AC	25
# OF MODULES	120
V.O.C(V)	37.8
MAX. MODULES/STRING	21
MIN. MODULES/STRING	14
ARRAY SIZE (unit)	15*8

source: Mouratidis et al. 2018

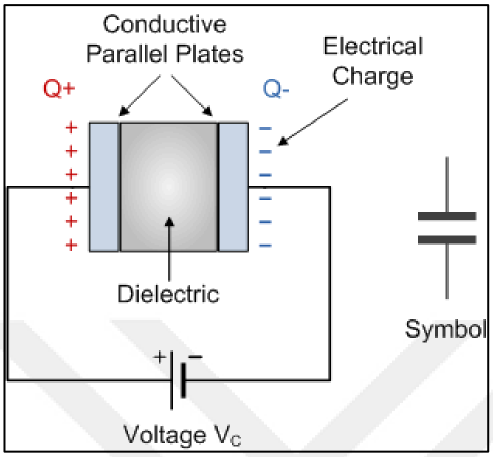
3.2.4 SCES Design

3.2.4.1 SCES technology overview

The new clean energy technologies will play an important role in prevailing over fossil fuel exhaustion as well as the pollution problem worldwide. With this in mind, electrochemical energy storage and conversion are considered eco-friendly storage technology. Furthermore, it is feasible and sustainable. Batteries, fuel cells, and super-capacitors are all considered electrochemical energy technologies. And they are all important in many static and dynamic applications comprising transportation and stationary and portable power. The issues that are related to energy technologies are such important issues due to the increasing demand for power sources.

In particular, super-capacitor technology will be handled in this section. In order to understand well this technology, the main concepts about capacitors should be elucidated. In detail, Capacitors are mainly energy storage devices have a structure like sandwich containing two conductive plates separated through a distance by an insulating material. Capacitors store the energy in a form of electrical energy as a charge across their plates. In order to charge Capacitors, an external voltage difference is applied across the two plates. The positive and negative charges accumulate gradually in the both plates. The positive charged plate is called positive electrode. while the negative charged plate is called negative electrode.

Figure 3.5: the main structure of the capacitor



source: Muller 2019

When the external voltage is disconnected, both the charges stay at their corresponding electrodes. In this way, the capacitor plays a role in separating electrical charges. The voltage difference between the two plates is called the capacitor cell voltage. When the electrodes are connected using a conductor with or without a load the discharging process takes place.

Both positive and negative charges can emit an electric flux on the surrounding area to create an electric field. The force lines of this field can be radiated outward in the case of positive charge, or inward in the case of negative charge. Therefore, the work done by the negative charge movement from its position through a distance toward the positive charge corresponds electric potential (V).

Capacitor plates will have equal and opposite magnitudes of charge. This indicates a zero net charge. These charges distribute uniformly along their surfaces. Charge Q (Q = |Q+| + |Q|) and potential V are related to each other through proportionality constant C:

$$Q = CV \tag{3.8}$$

Thus, the capacitor's proportionality constant stand for its capacitance. It is measured in farads (F) where 1 F equals 1 coulomb/volt (C/V). The previous equation can be rewritten as:

$$C = \frac{Q}{V} = \frac{A\,\varepsilon_0}{d} \tag{3.9}$$

The above equation demonstrates that capacitance is dependent on the dielectric constant of the dielectric material, the electrode surface area, and the distance between the two plates.

There are many types of capacitors according to way of manufacturing. Which differs according to the application of the capacitor or the desired capacity. For instance, if the application needs a variable capacitance, then the dielectric type of capacitors is the suitable option. Which are multi-plate air spaced that have a set of fixed plates and movable plates which move in between the fixed ones. The overall capacitance value is determined according to the position of the moving plates with respect to the fixed plates.

In addition to the dielectric type, Film Capacitors are also the most commonly obtainable of all types of capacitors in the small capacitance ranges (5pF - 100uF). Film Capacitors mainly consist of two types: Radial Lead Type and Axial Lead Type.

Above all, Electrolytic Capacitors are the most focused type because they are used when very huge capacitance values are required. The main concept in this type of capacitor is that instead of using a very thin metallic film layer for one of the electrodes, a semi-liquid electrolyte solution is used which functions as the second electrode. This electrode is usually the cathode.

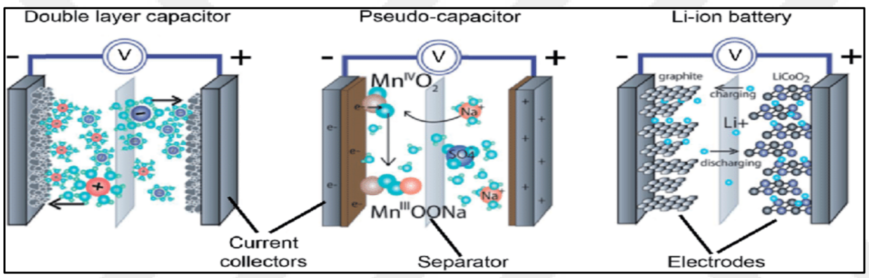
The dielectric is a tremendously thin layer of oxide. This insulating layer is very thin so that it is probable to make capacitors with a great value of capacitance with a small size as the distance between the plates is too tiny.

Indeed, all the previously mentioned principles are the basic knowledge to understand well the super-capacitors. in particular, the early concept of super-capacitors started from making an electric double-layer which is existed at the interface between the conductor and its contacting electrolyte solution. And this theory is considered the foundation of electrochemistry. Actually, electrochemistry is based on investigating an electrostatic interface between a charged electrode material and an electrolyte. The early models of electric double-layer at the interface between an electrode and an electrolyte solution were progressed using aqueous solutions. Afterward, models were extended into both aqueous with some modifications and non-aqueous electrolyte solutions.

In detail, super-capacitors use an electrolyte on either side of an insulator. When current is applied, ions build up on either side of the insulator and create a double layer of charge. In fact, what makes the super-capacitor truly superior is the distance between metal plates. In a normal capacitor the distance is between 10 and 100 microns ($1/1000$ millimeter). But in super-capacitor the distance is narrowed to $1/1000$ microns. Which means a lager electric field as well as a larger energy density.

Although the capacitance of double-layered super capacitors can be reached to 100,000 times than the normal capacitor. The ability of increasing the capacity of the super-capacitor is still available. By putting some electrochemically active materials for electrode. These materials provide much higher pseudo-capacitance than double-layer capacitance. Furthermore, the charge storage in pseudo-capacitance differs elementally from the electrostatic mechanism that regulates double-layer capacitance. In detail, faradic charge transfer in the electrode porous layer occurs in pseudo-capacitance. This is done through a thermodynamically and kinetically special electrochemical oxidation–reduction or redox reaction. The behavior of this reaction is analogous to electrochemical reactions in rechargeable batteries. However, both an electrochemically inert material and an electrochemically active substance. In other words, two processes happen in the charging and discharging: double-layer and the electrochemical redox process. The most common pseudo-capacitance materials are Nickel oxide, Ruthenium oxide, and Manganese dioxide.

Figure 3.6: Differences between the two types of SCs and conventional battery



source: Yu 2013

Actually, SC structure is so comparable to conventional batteries, they share the similar structure because of the existing of the electrolytic solution and electrodes except one big difference. In a SC, only permit electron movement between electrodes. In contrast, chemical reactions happen between the electrolytic solution and the electrodes in batteries. Figure 3.6 shows clearly different structures of battery and SCs.

3.2.4.2 SCES sizing

The bank of SC has to be suitable to the size of the load like any energy storage device. In this study, it feeds the load during the peak period. But vehicles do not come to the station at the peak time, sometimes they come late specially during weekends. Or they do not finish the charging process during the peak period.

Unlike battery bank in the residential side, the load of SC is clear, which is 4 EVs. Therefore, the calculation of bank capacity is easier. Thus, the capacities of the two scenarios can be like this:

$$\text{SCES CAPACITY} = \frac{\text{EV battery capacities } \times 30\%}{\max D.O.D} = \frac{[(34*2)+32+38] \ \times 30\%}{70\%} = 60 \text{ kWh} \quad \textbf{(3.10)}$$

4. STRUCTURE of THE ENERGY MANAGEMENT SYSTEM

4.1 FLOW CHART of EMS

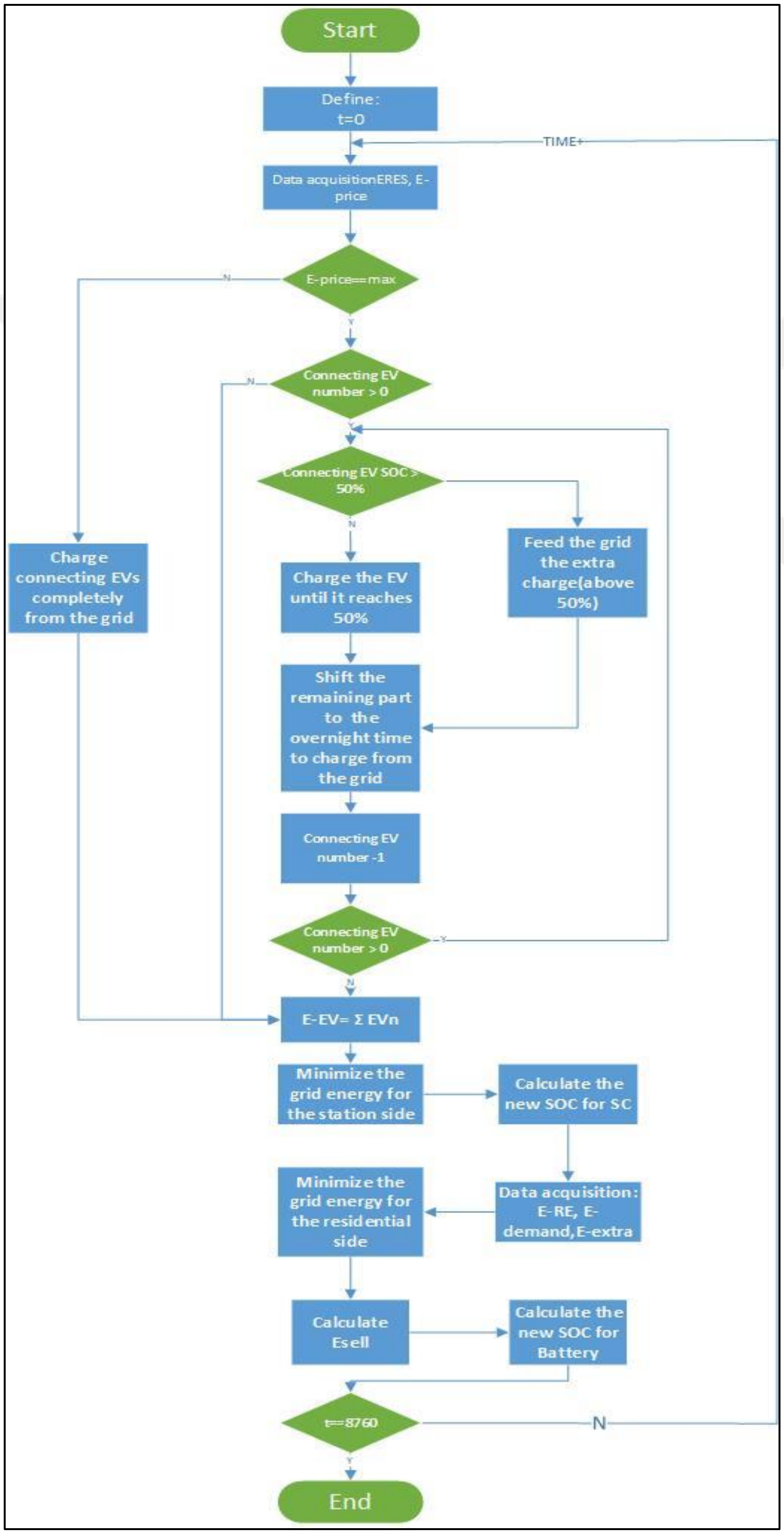
Figure 4.1 clarifies how the system works. It takes one hour as a time interval to update the grid's data and optimize again. The program should be initialized with some values such as the power limits and the starting time. After that, it reads the hourly values of the loads and sources then takes decisions according to the time slot that it is existed in. According to the power price. There are three time slots. Off-peak, mid-peak, and peak period.

Firstly, the charging station part is optimized. The SCES charges only from the PV generation. If there is a PV generation, the system checks the availability in the SCES, if there is a room for the whole amount of power, the power charges SCES. On the contrary, if the generated power from PV system cannot be charged partially or totally from SCES, then the extra portion of power goes to the residential part of the MG.

On the other hand, after considering the extra power from station side. EMS checks if there is a power generation from the residential PV cells, the priority is to use this power efficiently. If there is an availability in the battery to take this extra power, then the batteries are filled as much as possible. Afterward, if there is still an extra power, it is sold out to the grid. If the battery is in the mid-peak period, battery can feed the load unless it did not to the minimum SOC. When the time slot is on the peak period, the battery should feed the load until it reaches to the minimum SOC, if it reaches the minimum SOC it turns off until the end of the peak period. When the off- peak period comes the battery charges till it becomes full. However, this strategy shifts both residential load and EV load from the peak price. Furthermore, this strategy helps the grid dramatically to overcome the overload problems. In other words, a notable decrease in the overload will happen with this management strategy.

Along with EV charging, the flow chart in Figure 4.1 explains clearly the EMS strategy in arranging EV charging. In fact, when a certain EV connects to the station. The system checks its SOC. If it is above 50%, the EV battery gives the grid the portion of power that is higher than 50%. On the other hand, if the SOC is lower than 50%, the EV battery charges from SCES until reaches 50% SOC. Then in the low-price period of time, the remaining portion of each connected EV in the peak hour charges from the grid. If the EV connects to the grid after peak-time. It charges fully from the grid.

Figure 4.1: Flow chart of the energy management system.



4.2 MATHEMATICAL MODEL

Since there are two optimization processes in this grid hourly, the mathematical model of them should be clarified. Where; first part: defines the used equations for the charging station part of the MG during different day times. The aim of this model is to feed the EV load taking into consideration the efficient usage of the available energy hourly. Second part: defines the used equations for the residential load part of the MG. The of this model is to feed the residential load considering the efficient usage of the available energy hourly.

4.2.1 Optimization for The Station Part

Input data:

$E_{RES}(t)$: Energy from the PV cells on the roof of the station.

E_{ev}(t): EV load on the station.

E_price(t): electricity price.

E_{SC}(0): available energy in the SCES at the beginning of the simulation.

Objective function:

$$\text{Minimize}(\ E_{GRID1}(t) - G(t)\ ) \quad \textbf{(4.1)}$$

Constrains:

$$E_{GRID1}(\mathrm{t}) + F1(\mathrm{t})\, E_{SC}(t-1) + G(\mathrm{t}) = E_{ev}(\mathrm{t}) + F2\,(\mathrm{t})E_{SC}(t-1) \quad \textbf{(4.2)}$$

$$E_{SC-min} \leq E_{SC}(t-1) - F1(\mathrm{t})\, E_{SC}(t-1) \quad \textbf{(4.3)}$$

$$G(\mathrm{t}) \leq E_{RES}(\mathrm{t}) \quad \textbf{(4.4)}$$

$$\mathrm{E_{price}}(\mathrm{t}) \neq \max price \rightarrow F1(\mathrm{t}) = 0 \quad \textbf{(4.5)}$$

$$E_{RES}(\mathrm{t}) > E_{ev}(\mathrm{t}) \rightarrow F1(\mathrm{t}) = 0 \quad \textbf{(4.6)}$$

$$E_{RES}(\mathrm{t}) < E_{ev}(\mathrm{t}) \rightarrow F2(\mathrm{t}) = 0 \quad \textbf{(4.7)}$$

Calculated values

$F1(\mathrm{t})\, E_{SC}(t-1)$: Input Energy for SCES.

$F2$ (t) $E_{SC}(t-1)$: Output Energy from SCES.

$E_{GRID1}(t)$: Energy from the grid to the station.

$G(t)$: The portion from the station PV energy to the load or SCES.

Output data:

$$E_{SC}(t) = E_{SC}(t-1) + F2(t)\, E_{SC}(t-1) - F1(t)\, E_{SC}(t-1) \quad \textbf{(4.8)}$$

$$E_{extrta}(t) = E_{RES}(t) - G(t) \quad \textbf{(4.9)}$$

4.2.2 Optimization for The Residential Part

Input data:

$E_{RE}(t)$: Energy from the PV cells on the roof of the residential units.

$E_{extrta}(t)$: Energy taken from the extra PV generation from the station side.

$E_{DEMAND}(t)$: residential load.

$E_{BATTERY}(0)$: available energy in the battery at the beginning of the simulation.

Objective function:

$$\text{Minimize } (\mathrm{E}_{\mathrm{GRID2}}(\mathrm{t}) - Y(t)) \quad \textbf{(4.10)}$$

Constrains:

$$E_{GRID2}(t) + Z1(t)\, E_{BATTERY}(t-1) + Y(t) = \; E_{DEMAND}(t) + Z2(t)\, E_{BATTERY}(t-1) \quad \textbf{(4.11)}$$

$$E_{BATTERY-min} \leq E_{BATTERY}(t-1) - Z1(t)E_{BATTERY}(t-1) \quad \textbf{(4.12)}$$

$$E_{BATTERY}(t-1) + Z2(t)\, E_{BATTERY}(t-1) \leq E_{BATTERY-max} \quad \textbf{(4.13)}$$

$$Y(t) \leq E_{RE}(t) + E_{extrta}(t) \quad \textbf{(4.14)}$$

$$\mathrm{E}_{\mathrm{price}}(\mathrm{t}) = \min price \;\rightarrow\; Z1(\mathrm{t}) = 0 \quad \textbf{(4.15)}$$

$$E_{RE}(t) > \; E_{DEMAND}(t) \rightarrow \; Z1(\mathrm{t}) = 0 \quad \textbf{(4.16)}$$

$$E_{RE}(t) < E_{DEMAND}(t) \wedge t \neq 0 \rightarrow Z2(\mathrm{t}) = 0 \quad \textbf{(4.17)}$$

$$E_{BATTERY}(t-1) = E_{BATTERY-min} \wedge t = 0 \rightarrow Z2(\mathrm{t}) = \frac{E_{BATTERY-max} - E_{BATTERY}(t-1)}{E_{BATTERY}(t-1)} \quad \textbf{(4.18)}$$

Calculated values:

$\mathrm{Z1(t)\ E_{BATTERY}(t-1)}$: Output energy from the battery.

$\mathrm{Z2(t)\ E_{BATTERY}(t-1)}$: Input energy for the battery.

$\mathrm{Y(t)}$: The portion from the residential PV generation to the load or battery.

$E_{GRID2}(t)$: Energy from the grid to the residential part.

Output data:

$$\mathrm{E_{sell}(t)} = [\mathrm{E_{RE}(t)} + E_{extrta}(t)] - \mathrm{Y(t)} \quad \textbf{(4.19)}$$

$$\mathrm{E_{BATTERY}(t) = E_{BATTERY}(t-1) + Z2(t)\ E_{BATTERY}(t-1) - Z1(t)\ E_{BATTERY}(t-1)} \quad \textbf{(4.20)}$$

Accordingly, the variables of the optimization model are calculated hourly. The whole energy management process is done by hourly optimization which is explained in the flow chart. However, this mathematical model is entered to Gurobi optimizer in order to get the hourly results. Gurobi is a mathematical solver that does some processes to solve optimization models, and it is defined in detail in the sub-section 5.3.

5. SIMULATION and RESULTS

5.1 INPUT DATA

In order to see the performance of the proposed energy management strategy for a residential microgrid, the following input data are used to simulate the system for one year.

Figure 5.1 : SOC of EV1 when it arrives to station during all the year

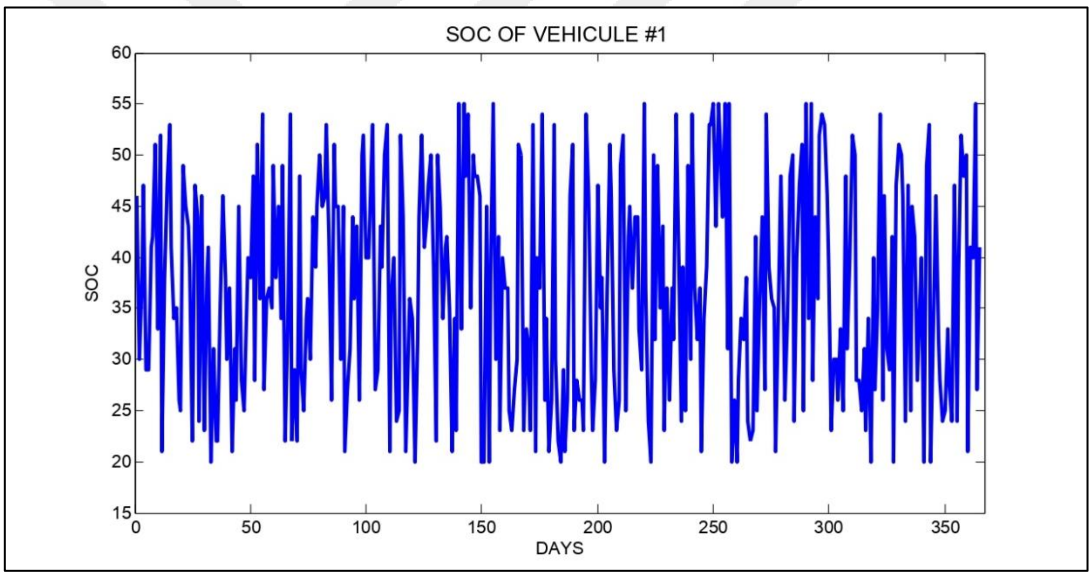


Figure 5.2 : SOC of EV2 when it arrives to station during all the year

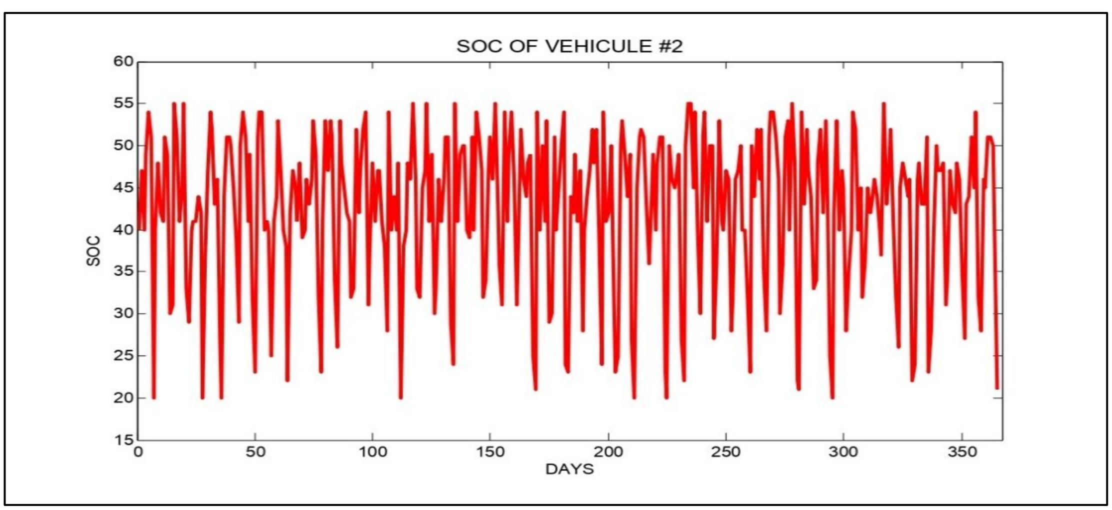


Figure 5.3 : SOC of EV3 when it arrives to station during all the year

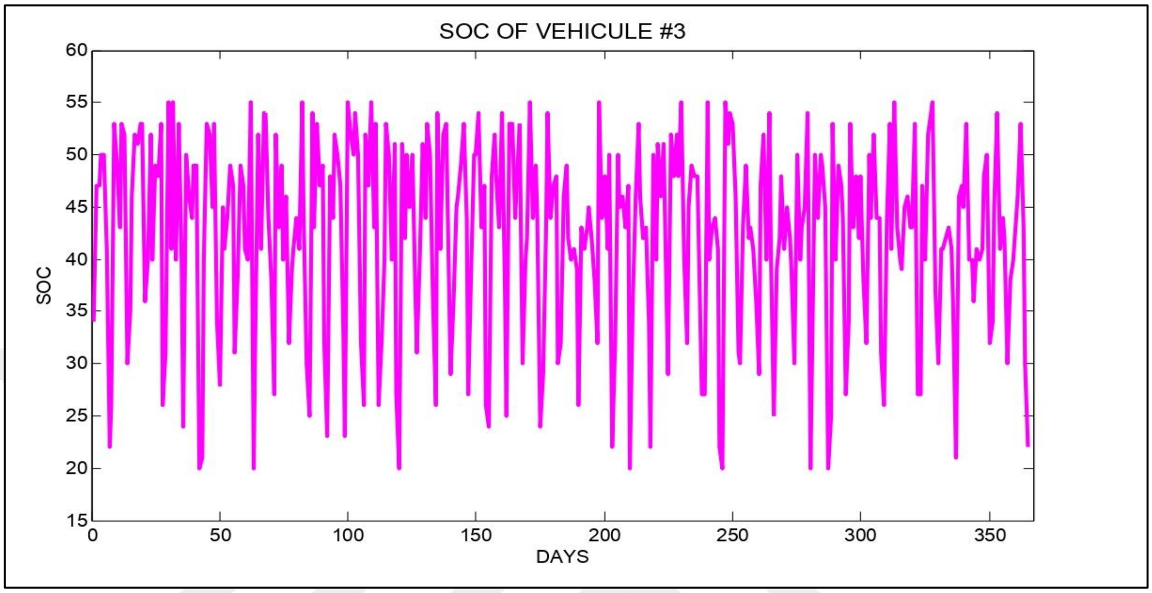


Figure 5.4: SOC of EV4 when it arrives to station during all the year

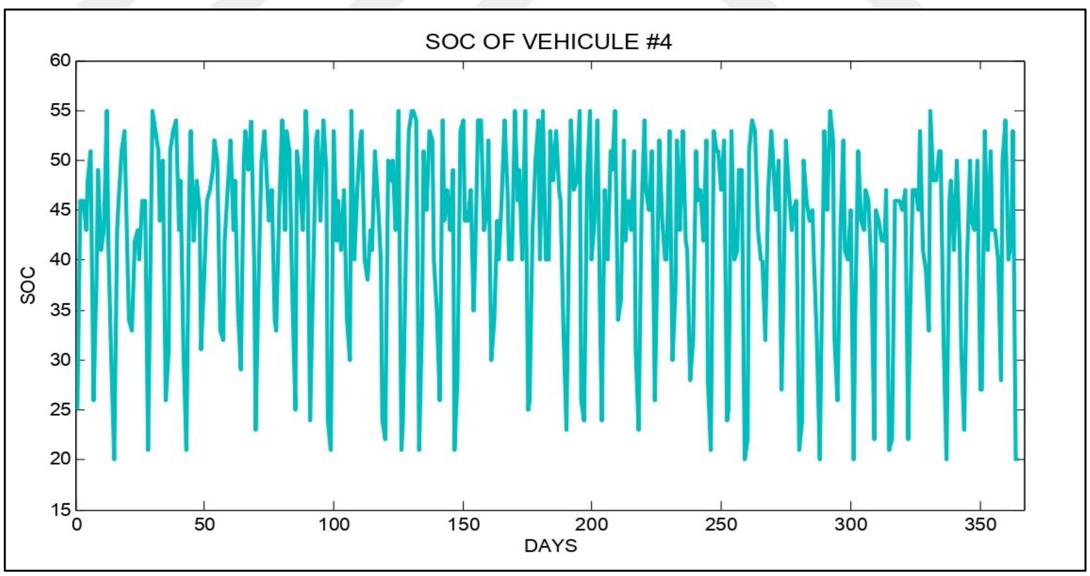


Figure 5.5: Residential daily load

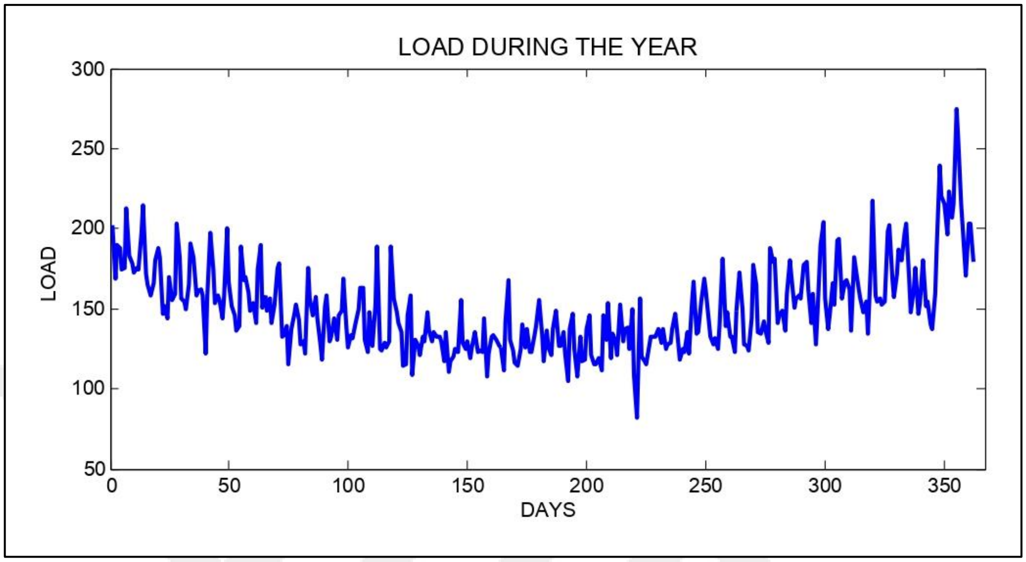


Figure 5.6: Residential hourly load

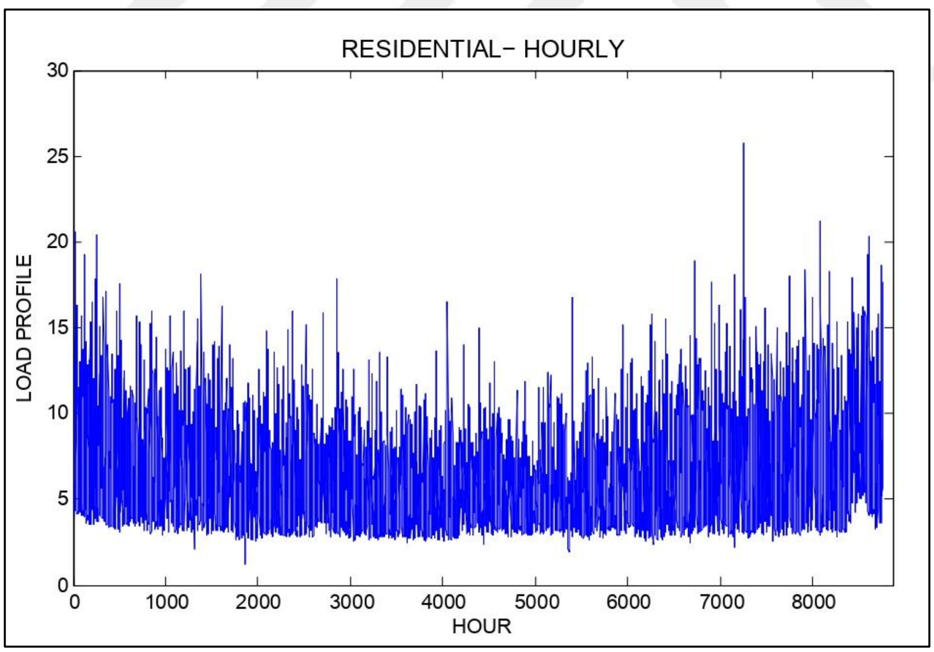


Figure 5.7: Residential hourly PV generation

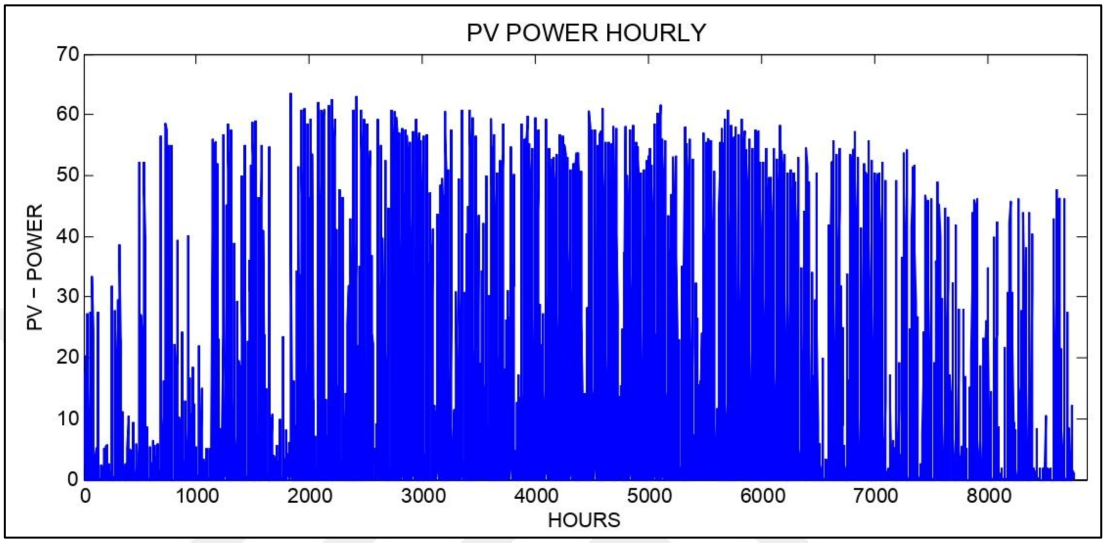
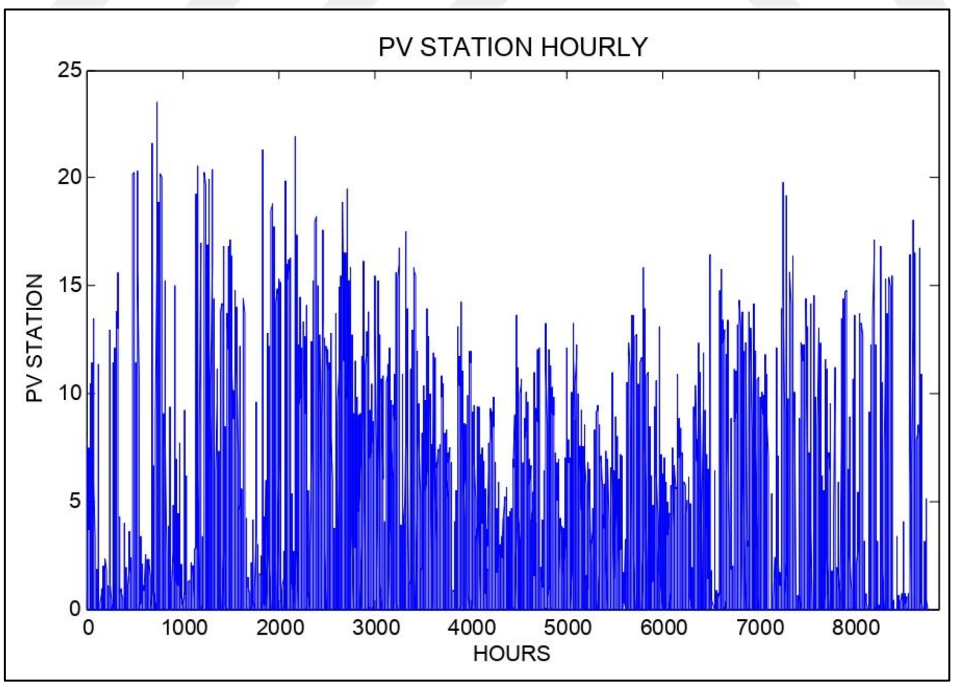


Figure 5.8: Station hourly PV generation



The above figures show the input data for the simulation. All of them are one-year data to show the effects of load and weather changes through the year. However, the specifications of these inputs are discussed in detail in the chapter 3.

For the charging station part, the input data are the EV load as well as PV panels hourly generated power. The EV load is represented by the daily SOC as it is shown in Figure5-1, Figure5.2, Figure5.3, and Figure5.4. In addition to the EV load, Figure5-8 shows the hourly data of the PV generated power in the station array.

Likewise, there are two inputs for the residential part. First, the hourly residential load which is shown in Figure5-6. Second, the PV generation from the residential units in Figure5.7. Furthermore, the system takes the price of the electricity hourly.

5.2 OPERATION SCENARIOS

Three operation scenarios are simulated with the given energy management strategy. They are given in Table 5-1. In each scenario, four EVs are used for the given microgrid system. The types of the EVs are Hyundai IONIQ-BMW i3-VW e-Golf.

Table 5.1: Operation scenarios

Scenario	1	2	3
Residential battery(kWh)	145	262	145
SCES(kWh)	60	60	-
Explanation	sizing the residential battery according to the average residential load	sizing the residential battery according to the max. residential load	Without considering any management scenario

The aim of making several scenarios is to show the effects of changing some physical or structural elements on the system. However, scenario is expected to be a terrible case which affects on the grid concerning to the overloading issue. Especially in the peak period. At that time the power cost is the highest cost.

On the other hand, both scenarios one and two consider a management strategy along with SCES. The difference between them is that scenario2 has a larger BSS size because it is shaping the peak residential load.

5.3 SIMULATION ENVIRONMENT

5.3.1 Mathematical Optimization Overview

Mathematical optimization or mathematical programming is an intensely powerful prescriptive analytics technology that capacitates users to solve complex mathematical problems and make better use of available resources and data. Mathematical programming is the invention of linear programming in 1947 by George Dantzig. It allows you to catch the key features of a complex real-world problem as an optimization model. An optimization model is comprised of relevant objectives, variables (decisions in your optimization process) and constraints to suggest a solution that creates the best possible result. A math programming solver is the computational engine that reads the optimization model and then gives an optimal feasible solution.

Mathematical optimization entails three steps:

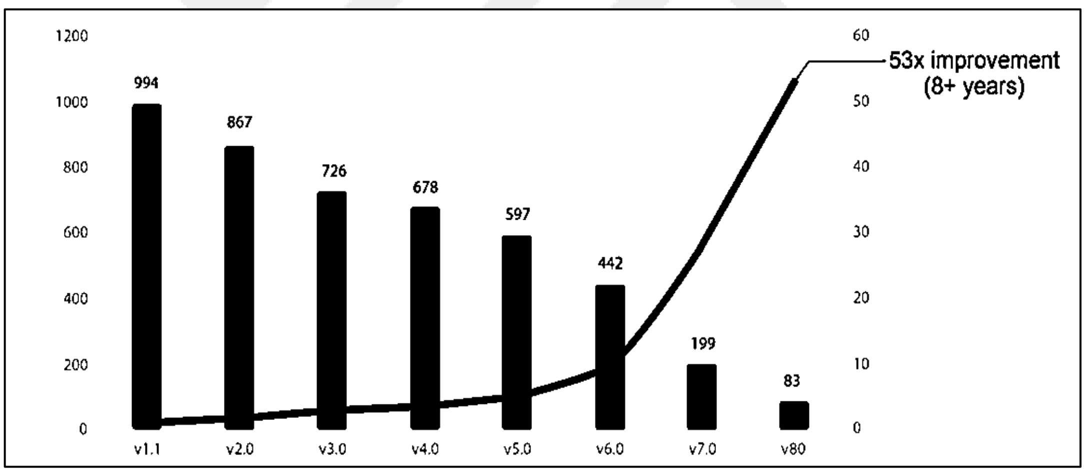
a. The formulation of real-world problems in detailed mathematical terms.
b. Develop algorithm that solve these mathematical programming models.
c. Use software and hardware to develop applications.

Mathematical programming technologies are being used in many fields such as scientific research in order to know the best choices or physical quantities for a certain problem. It is also used in the business field. And it can provide many benefits for companies like capture the important decisions in the business process, capture the resources possibly spent by these decisions, capture the potential conflicts between these activities, and cuggest a plan of action that maximizes the overall efficiency of the process. It can be used in miscellaneous types of companies and institutes such as Electrical power distribution, finance, government, logistics, manufacturing, and sports scheduling.

5.3.2 Gurobi

Gurobi is a mathematical solver that considers trillions or more possible combinations to find the best one automatically. Thus, it is used as a fully automated tool to make decisions without human interpolation. Gurobi uses simplex method which is invented by George Dantzig. Simplex method is a systematic approach to traverse the vertices of the polyhedron that contains the feasible solutions of a linear programming problem as well as the optimal solution. Gurobi has the best performance in the market. The improvement in its performance can be shown in Figure 5.9.

Figure 5.9: Gurobi growth over eight years



source: Gurobi 2020

The user of Gurobi does not need to worry about how to solve the optimization problem at hand, this is done automatically by Gurobi behind the scenes. The user only needs to have an efficient mathematical model that captures the main characteristics of the optimization problem and the required data for the model.

5.4 SIMULATION RESULTS

Table 5.2: Comparison for the outputs among different scenarios

Month	E_{GRID1}-Residential (kWh)			E_{GRID2}-station (kWh)			Esell (kWh)			Ebuy(GRID1+GRID2) - Esell (kWh)		
	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
1	3635	3246	5547	1733		-	1863	1473	1833	3506	3506	3714
2	2256	2085	4292	1616		-	3710	3538	4010	162	162	282
3	1812	1445	4222	1721		-	6454	6086	6979	-2921	-2921	-2757
4	718	718	3743	1702		-	9193	9193	10368	-6772	-6772	-6624
5	656	656	3706	1754		-	8875	8875	10052	-6465	-6465	-6347
6	604	604	3411	1710		-	9245	9245	10307	-6931	-6931	-6896
7	671	671	3760	1779		-	10251	10251	11322	-7801	-7801	-7562
8	820	710	3707	1792		-	8798	8688	9784	-6185	-6185	-6077
9	825	714	3931	1727		-	7307	7375	8602	-4755	-4934	-4671
10	1708	1706	4561	1791		-	6123	6012	7083	-2624	-2515	-2521
11	2075	1872	4451	1718		-	3069	2866	3601	724	724	850
12	3963	3304	6220	1844		-	2486	1908	2753	3321	3239	3467

Table 5.3: The ratio between SCES discharged power and the residential peak load

month	SC discharged Energy (kWh)	Residential peak period load(kWh)	SC to peak period load percentage
1	375	1870	20%
2	341	1489	23%
3	348	1444	24%
4	381	1298	29%
5	312	1238	25%
6	347	1117	31%
7	429	1152	37%
8	340	1241	27%
9	377	1400	27%
10	368	1588	23%
11	372	1683	22%
12	355	1919	18%

Table 5.4: Energy from the grid during peak times

Energy from the grid during peak times (kWh)		
S1	**S2**	**S3**
643	345	4446
361	182	3834
147	52	3241
0	0	2817
0	0	1533
0	0	1659
0	0	1880
9	0	2329
43	34	3092
254	156	4093
224	185	4231
744	458	4329

This section represents the simulation output and the feedback on them. Table 5.2 shows the energy flow from and to the MG in each scenario. E-buy represents the amount of energy taken from the grid. Furthermore, E-sell represents the total sold power from the residential side as well as the station side, which sells around 24 kWh monthly at the peak period of the day.

Scenarios 1 and 2 show clearly the advantages of the management scenario. Because the energy taken from the grid is less in the EMS situation. In the warm months, MG sells more to the grid because of the increase in PV generation. Scenario 2 also has more benefits slightly because of the higher capacity (around 1.6). At the same time, this higher capacity also has a higher initial cost. Therefore, the battery size in scenario 1 is the best size for this case study.

Furthermore, Table 5.3 shows the monthly load afforded by SCES as well as the ratio of this portion to the residential load. This table shows a relatively high ratio which ranges between 18percent and 37 percent. The fed energy from SCES is used for charging EVs that have less than 50 percent SOC. Likewise, Table 5.4 shows the benefits of EMS but in a different way. It shows the loading on the peak without considering any management scenario in comparison with EMS approach. The loading without management is enormous because of the existing of EV load as well as the possible charging of the BSS during this period. As a result, this EMS successfully manages the MG considering lower possible loading at the peak time.

Figure 5.10: Battery charging and discharging process in scenario1 during the year

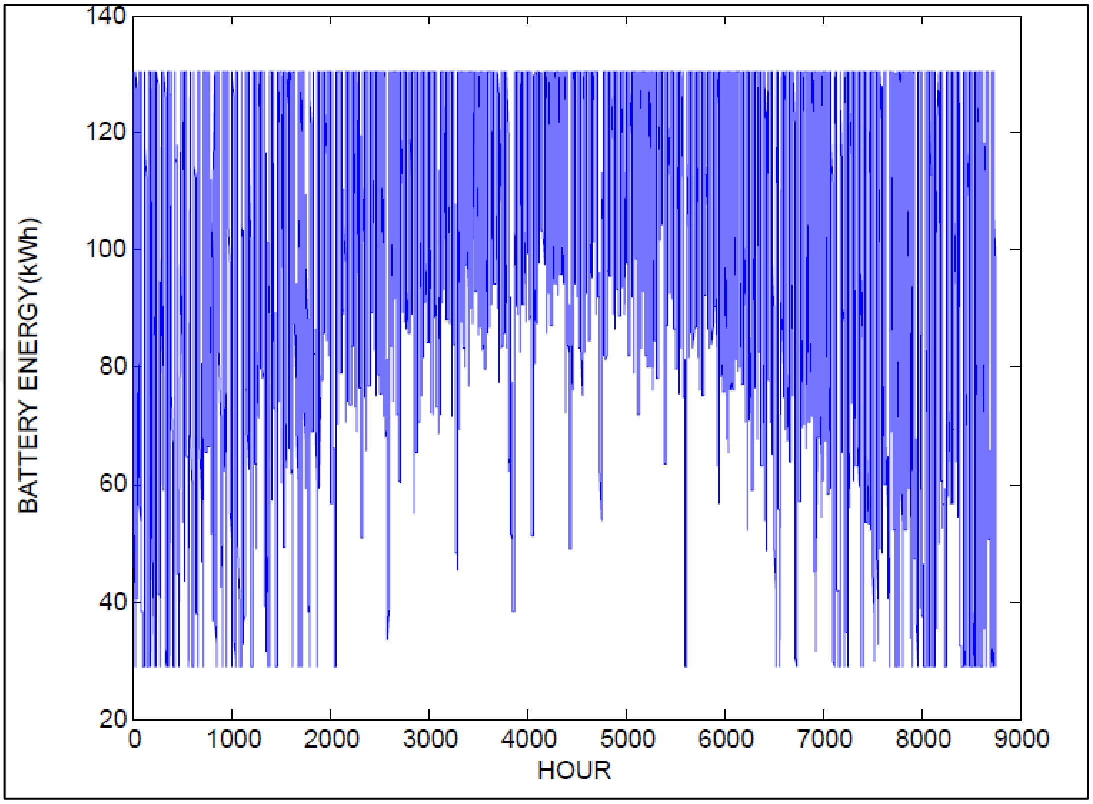


Figure 5.11: Battery charging and discharging process in scenario2 during the year

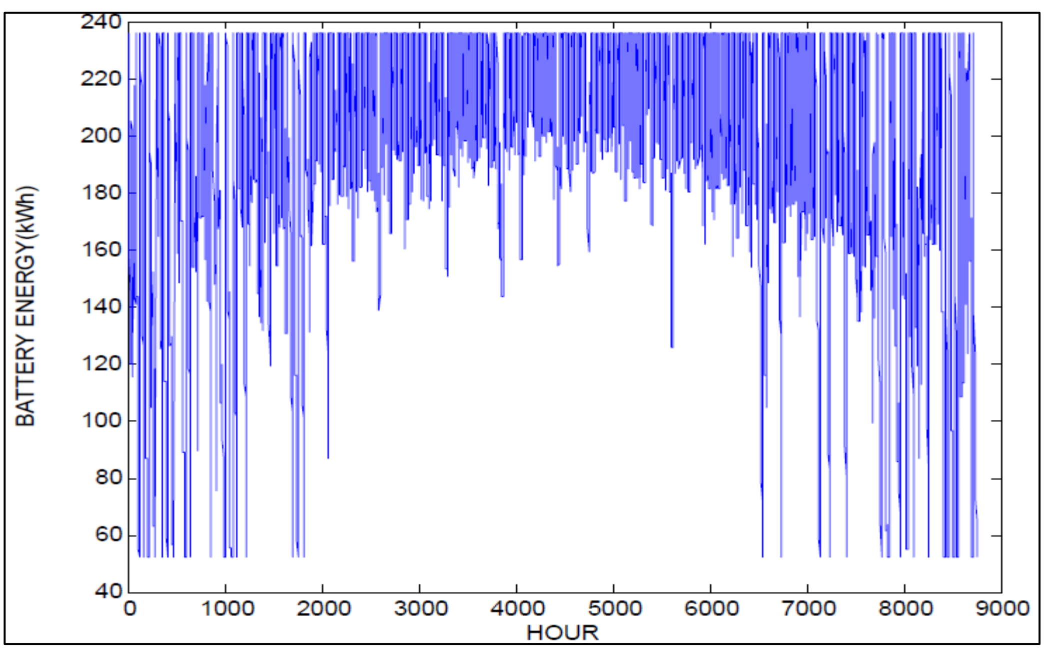


Figure 5.12: Battery charging and discharging process in scenario3 during the year

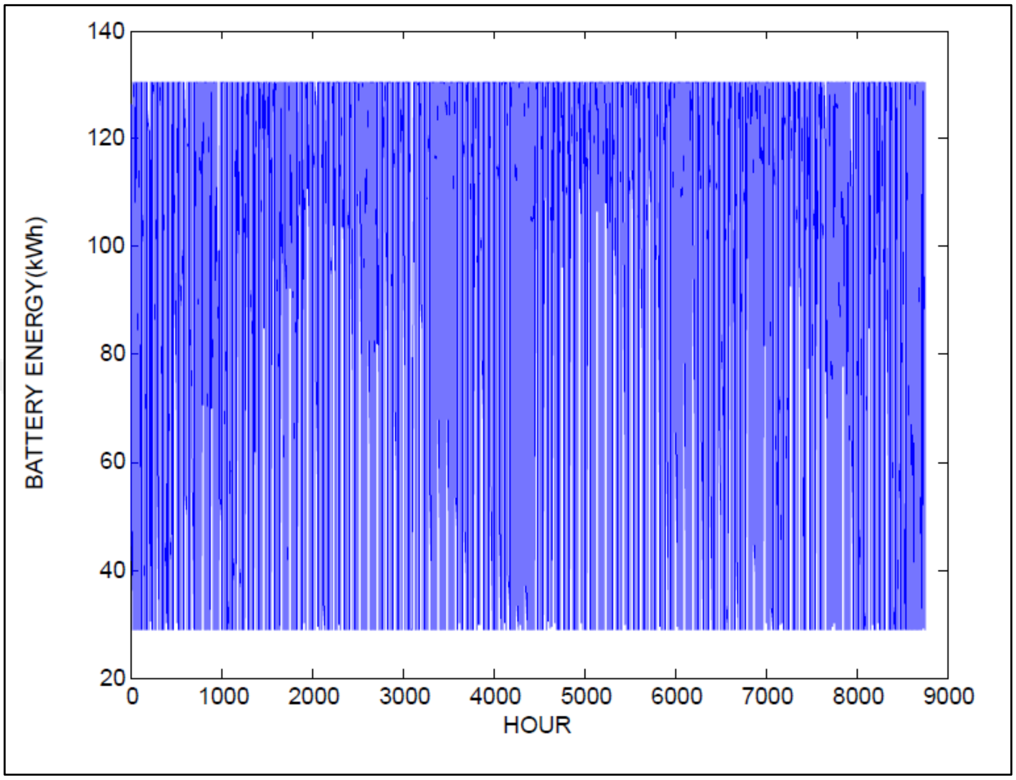
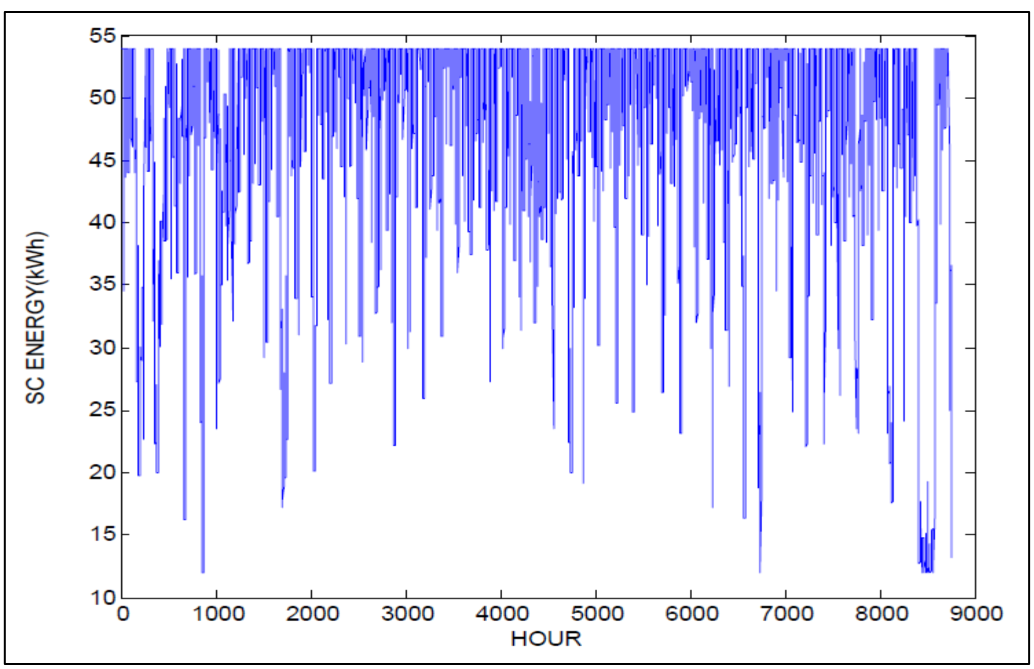


Figure 5.13: SCES charging and discharging process during the year



Likewise, the figures explain some detail that represents the importance of this EMS. In particular, Figure 5.10, Figure 5.11, and Figure 5.12 show the charging and discharging behaviors of the residential battery in the different scenarios. Scenarios 1 and 2 have approximately the same shape with different values due to difference in battery capacities. Whereas scenario 3 has a different shape. Since the charging and discharging process is not organized in scenario 3, the cycling number each day is higher than the other two scenarios, which means a shorter lifetime for the battery. In a like manner, Figure 5.13 shows the charging and discharging process for the SCES during the year.

Figure 5.14: Battery charging and discharging process per day in scenario1 in the middle of each season

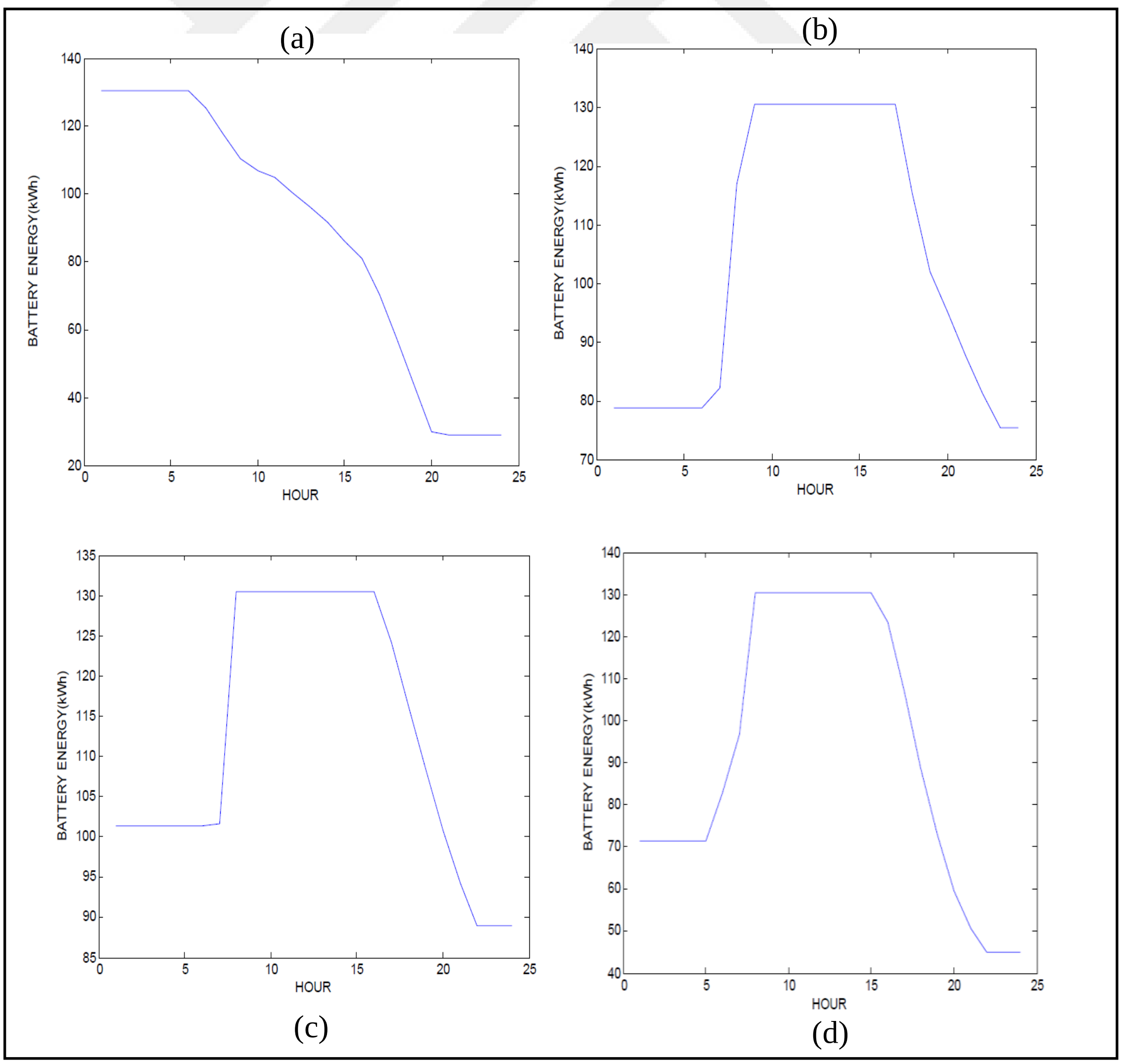


Figure 5.15: Battery charging and discharging process per day in scenario2 in the middle of each season

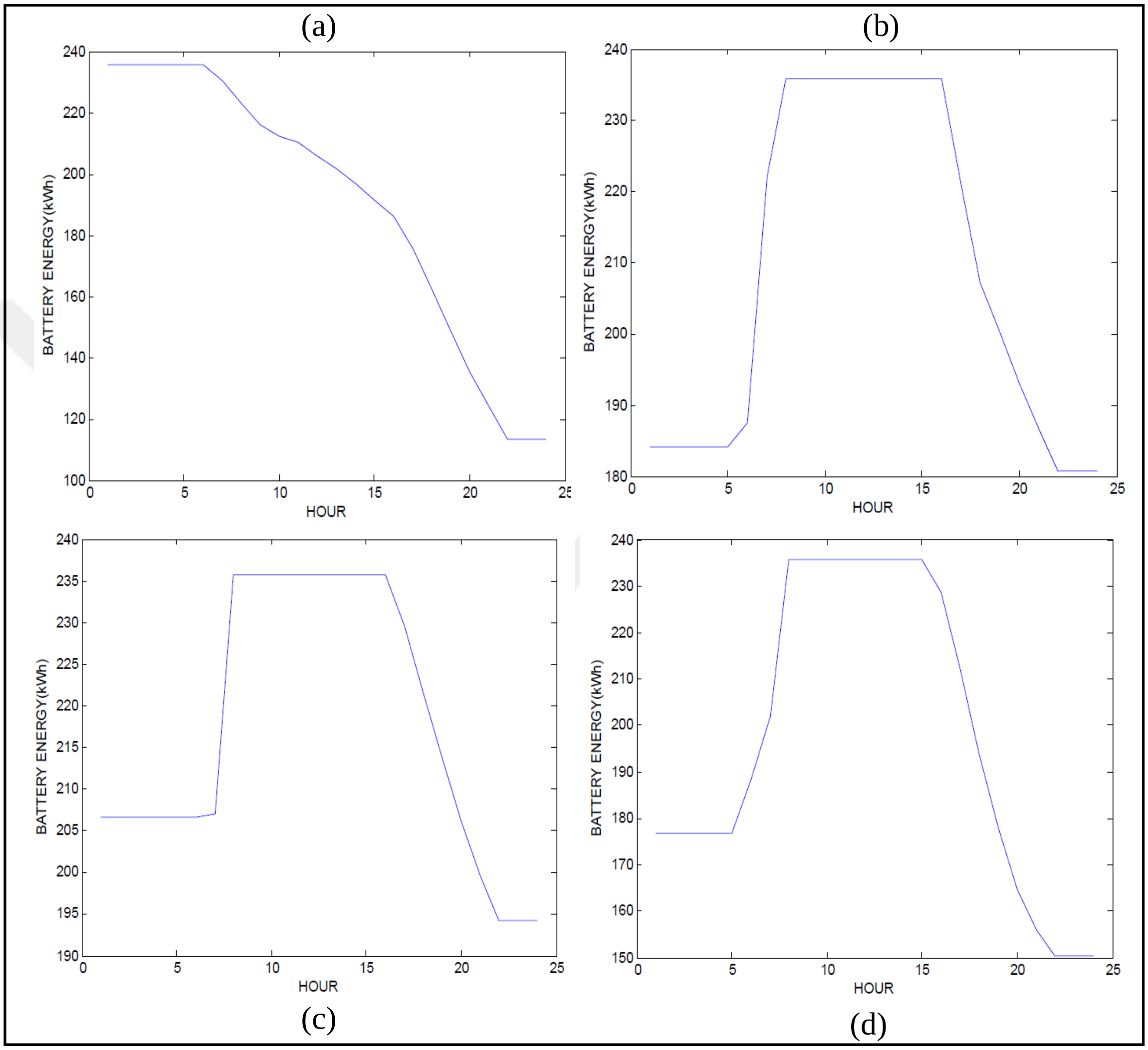


Figure 5.16: Battery charging and discharging process per day in scenario3 in the middle of each season

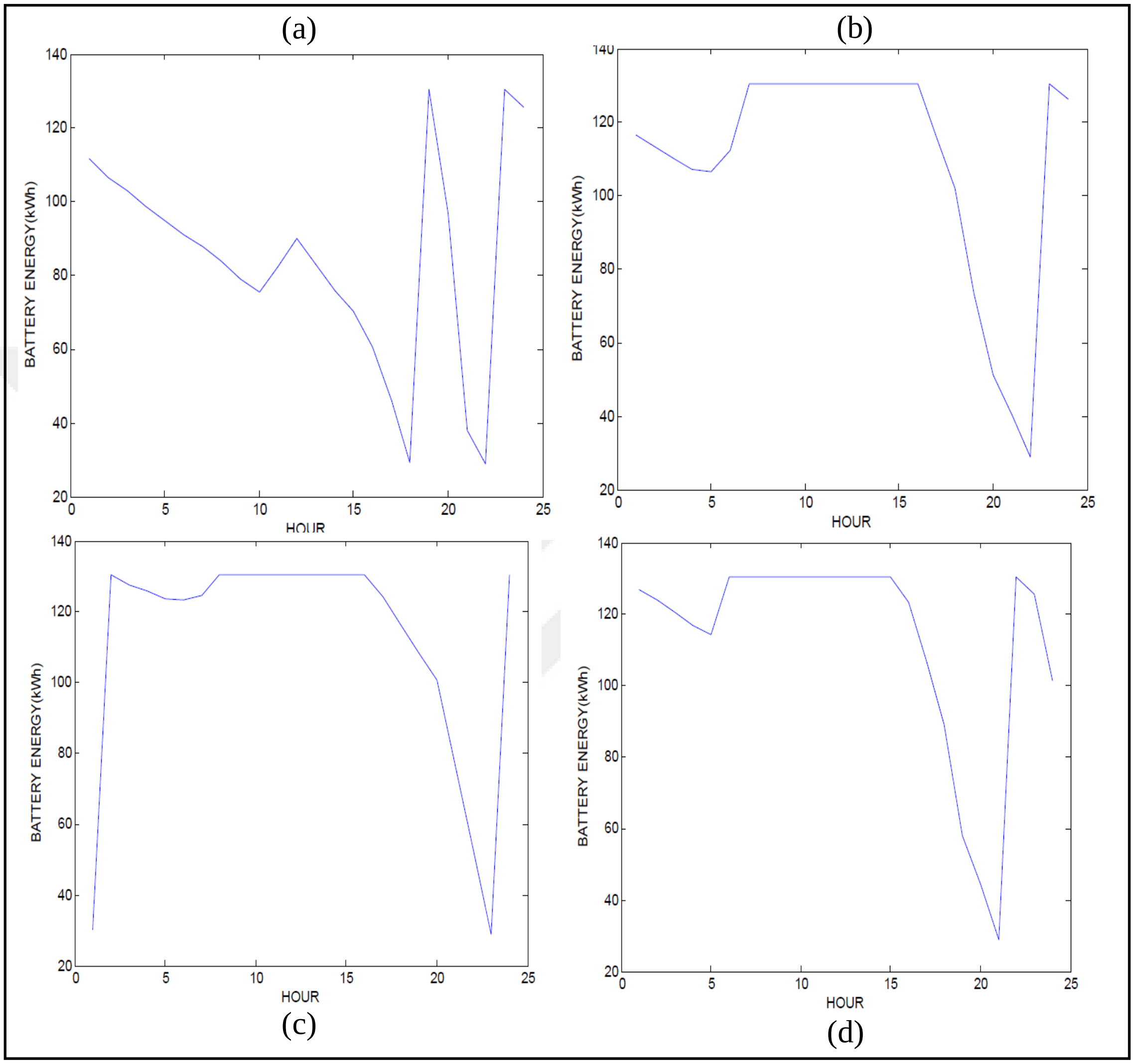
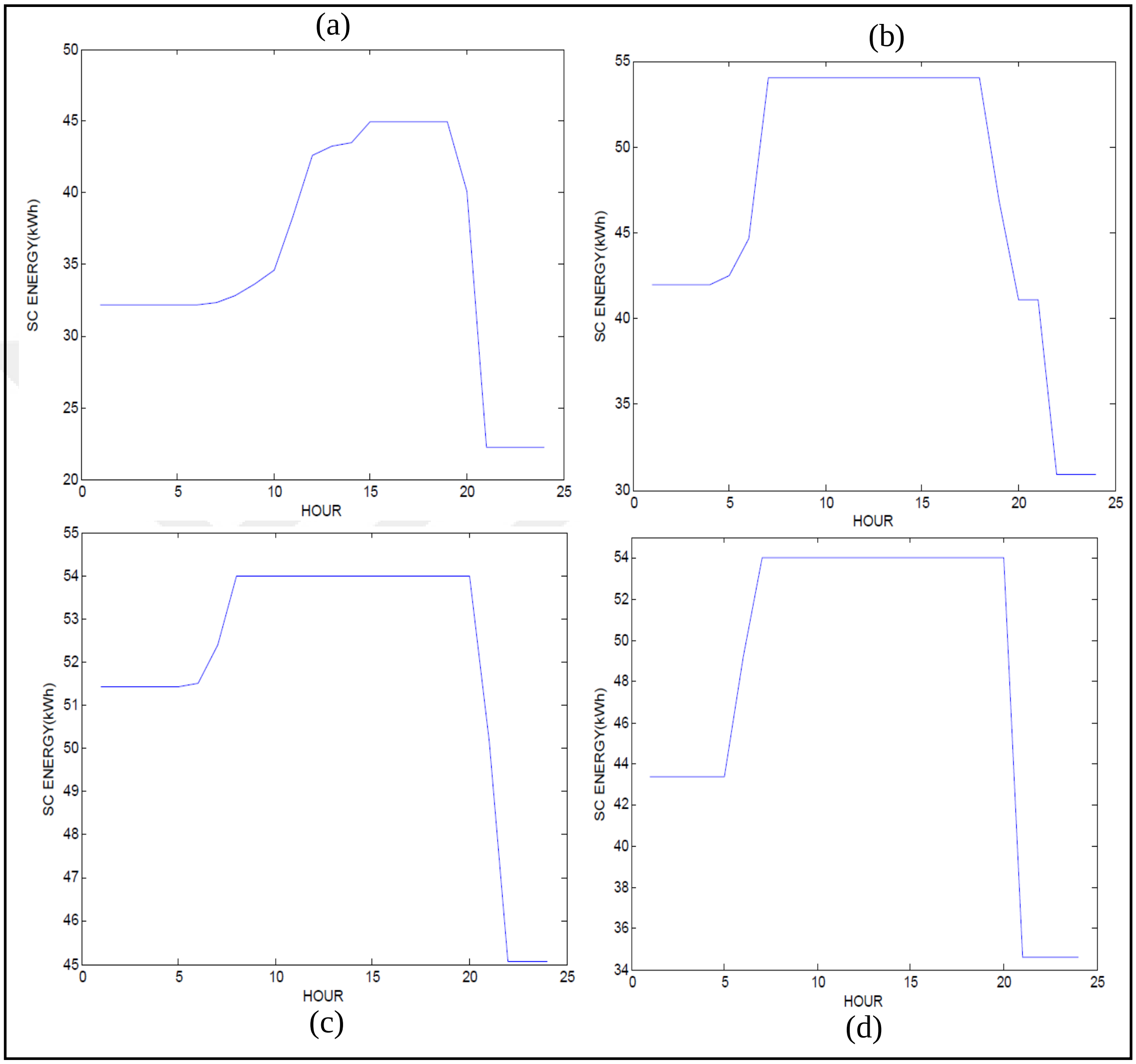


Figure 5.17: SCES charging and discharging process per day in the middle of each season



To go through daily charging detail. Figure 5.14, Figure 5.15, Figure 5.16, and Figure 5.17 show the charging and discharging process through one day in the middle of each season for both the three BSS scenarios and SCES, respectively. In each one, (a) represents the winter, (b) represents the spring, (c) represents the summer, and (d) represents the fall. For BSS, the shortage in PV energy is obvious in the winter term. In addition to this, the higher cycling number is more clear in Figure 5.16. Concerning SCES, it is noticed in Figure 5.17 that it charges smoothly and discharges faster because of the short discharging period (peak hours) with a high EV load.

6. CONCLUSION

In this study, an EMS is proposed for a MG consists of two parts. The first part is the residential part which has PV arrays on the roof of the residential units. Furthermore, a central backup BSS is applied for this PV system. Likewise, the other part of this MG is a fast charging EV station. This station has a SCES system to shift the EV load from the peak hour in case that the EV has less than 50 percent SOC. If it has a higher SOC the extra portion of the energy is fed to the grid. Then the EV can be charged fully after the peak hour period. In addition to this, the station has its PV array. Furthermore, SCES could feed EV batteries to reach 50 percent SOC.

As a result, simulations show an improvement in the usage of the energy. This portion of energy is between (18-37) percent of the residential load during the peak period. If the EVs charge without the proposed management strategy, the loading on the grid in this period increases dramatically. In addition to this, EVs are charging with lower costs because EVs charge either from SCES in the peak time or the grid overnight by taking into account their SOCs. Moreover, EVs with a SOC more than 50 percent feed the grid around 24 kWh per month during peak periods. In the residential part, although scenario 2 has around 1.6 higher BSS capacity than the BSS in the scenario 1. Scenario 2 shows slightly better results taking into consideration the higher cost. Therefore, the battery size of scenario 1 (145kWh) is the best size for this case study. It means that the battery size should be chosen by considering average residential load. As future work, SCES can also be used to regulate the voltage levels during the daytime.

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