Plug-in Electric Vehicles charging methods comparison in Electric Power Systems with high renewable energy sources penetration

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Abstract

Sales of electric vehicles have skyrocketed globally in recent years, mostly as a result of the environmental advantages of electrification. There are no issues with the national energy system as long as electric vehicle penetration rates are kept low. However, if these tariffs continue to rise and the rate at which vehicles are charged is not controlled, the electrical network may become overloaded and unable to meet demand for electricity. At the same time, it starts to act as a flexible load, which will benefit the system at times of high electricity demand.

The goal of this diploma thesis is to increase the overall use of RES energy and even out the daily load by simulating the charging needs of electric vehicles during the day as well as their capacity to send energy back to the grid while they are parked. However, in order to approximatively determine the effects that penetration scenarios will have on the grid, time series of the daily load and the daily production of Renewable Energy Sources for the Crete system are used.

According to how optimistic the electrification adaptation will be, four distinct penetration scenarios are investigated. Simple direct charging, smart charging and vehicle to grid charging with the option of delivering energy to the grid were used as the charging techniques in order to compare the outcomes.

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Part I

Theoretical Analysis

CHAPTER 1

Electric Vehicles (EVs)

1.1 Electric Vehicles and their types

A vehicle that uses one or more electric motors for propulsion is referred to as an electric vehicle (EV). It can be driven independently by a battery, a collector system, or electricity from extravehicular sources (sometimes charged by solar panels, or by converting fuel to electricity using fuel cells or a generator). Road and rail vehicles, surface and underwater watercraft, electric airplanes, and electric spacecraft are all examples of EVs.

EVs first appeared in the middle of the 19th century, when electricity was one of the most popular forms of motor vehicle power. They offered a level of comfort and convenience of use that gasoline cars of the day were unable to match. For almost 100 years, internal combustion engines (ICE) predominated as the primary means of propulsion for cars and trucks, but electric power remained prevalent in other vehicle types, such as trains and smaller vehicles of all kinds.

Due to technology advancements, a greater emphasis on renewable energy, and the possibility to lessen the impact of transportation on climate change, air pollution, and other environmental issues, EVs have had a comeback in the 21st century.

Due to technology advancements, a greater emphasis on renewable energy, and the possibility to lessen the impact of transportation on climate change, air pollution, and other environmental issues, EVs have had a comeback in the 21st century. Electric vehicles are ranked among the top 100 modern options to combating climate change by Project Drawdown.

Internal combustion engine vehicles often only get their energy from one or two sources, which are typically non-renewable fossil fuels. Regenerative braking, which restores electricity to the on-board battery in place of the kinetic energy generally lost during friction braking as heat, is a major benefit of electric vehicles. [6]

1.1.1 Battery Electric Vehicles (BEVs)

A battery and an electric drive train power a complete battery electric vehicle (BEV), also known as an all-electric vehicle (AEV). These particular electric vehicles lack an ICE. A sizable battery pack that can hold electricity is charged by connecting to the power grid. The battery pack then fuels one or more electric motors that power the electric vehicle.

Working Principles of BEV

- Power is converted from the DC battery to AC for the electric motor
- The accelerator pedal sends a signal to the controller which adjusts the vehicle's speed by changing the frequency of the AC power from the inverter to the motor
- The motor connects and turns the wheels through a cog
- When the brakes are pressed or the electric car is decelerating, the motor becomes an alternator and produces power, which is sent back to the battery

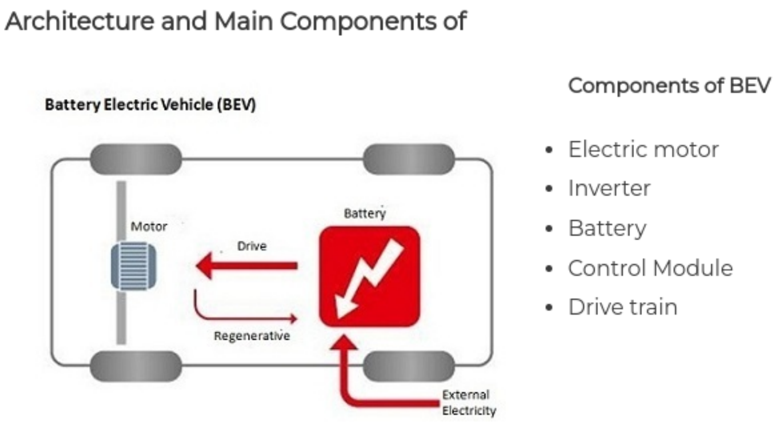

Figure 1.1. Battery Electric Vehicle (BEV) [7]

1.1.2 Hybrid Electric Vehicles (HEVs)

These hybrid vehicles are frequently referred to as parallel hybrids or normal hybrids. HEVs have an ICE in addition to an electric motor. In these sorts of electric vehicles, the motor is powered by batteries instead of the internal combustion engine, which runs on fuel (gasoline and other forms of fuel). The transmission, which turns the wheels, is turned by both the gasoline engine and the electric motor at the same time. HEVs differ from BEVs and PHEVs in that their batteries can only be charged by an internal combustion engine, the rotation of the wheels, or a combination of the two. The battery cannot be recharged from outside the system, such as from the electrical grid, because there is no charging port.

Working Principles of HEV

- Has a fuel tank that supplies gas to the engine like a regular car
- It also has a set of batteries that run an electric motor
- Both the engine and electric motor can turn the transmission at the same time

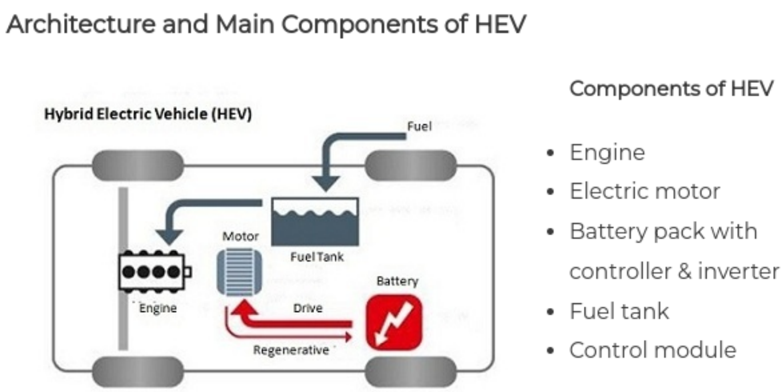

Figure 1.2. Hybrid Electric Vehicle (HEV) [7]

1.1.3 Plug-in Hybrid Electric Vehicles (PHEVs)

A PHEV is a hybrid vehicle that has both an ICE and a motor, and is frequently referred to as a series hybrid. This class of electric vehicles has a range of fuel options. This category of electric vehicles is propelled by a rechargeable battery pack and either a conventional fuel (like gasoline) or an alternative fuel (like biodiesel). Electricity can be used to recharge the battery by plugging it into an outlet or an electric vehicle charging station (EVCS).
PHEV typically can run in at least two modes:

- All-electric Mode, in which the motor and battery provide all the car's energy
- Hybrid Mode, in which both electricity and gasoline are employed.

Working Principles of PHEV

PHEVs normally start in electric-only mode and continue to run on energy until their battery pack runs out. When they reach highway cruising speed, which is often

above 60 or 70 miles per hour, some models switch to hybrid mode. When the battery runs out, the engine kicks in and the car starts running like a regular, non-plug-in hybrid.
An internal combustion engine or regenerative braking can charge PHEV batteries in addition to hooking into an external electric power source. The electric motor functions as a generator during braking, utilising the energy to recharge the battery. Smaller engines can be employed since the electric motor augments the engine's power, improving fuel efficiency without sacrificing performance.

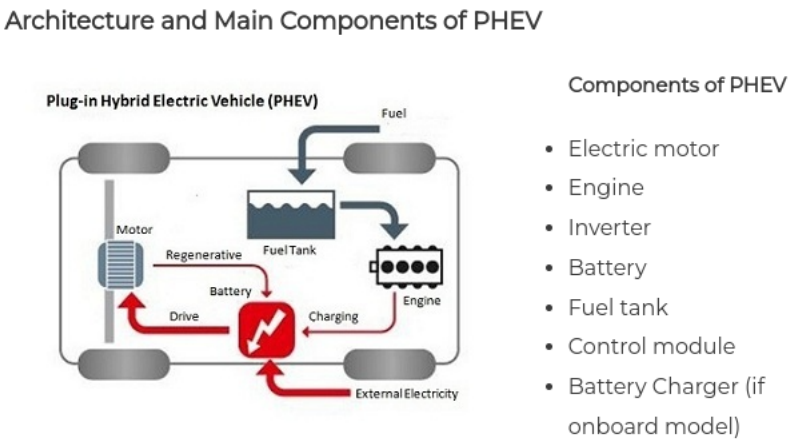

Figure 1.3. Plug-in Hybrid Electric Vehicle (PHEV) [7]

1.1.4 Fuel Cell Electric Vehicles (FCEVs)

Fuel cell electric vehicles (FCEVs), often referred to as zero emission vehicles (ZEVs) or fuel cell vehicles (FCVs), are a subset of electric cars that use "fuel cell technology" to produce the electricity needed to power them. The chemical energy of the gasoline is directly turned into electric energy in this sort of vehicle.

Working Principles of FCEV
The working principle of a 'fuel cell' electric car is different compared to that of a 'plug-in' electric car. This types of electric cars is because the FCEV generates the electricity required to run this vehicle on the vehicle itself.

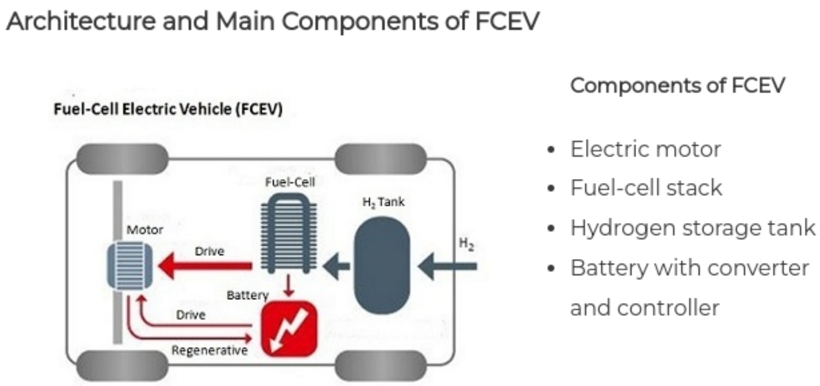

Figure 1.4. Fuel Cell Electric Vehicle (FCEV) [7]

1.2 Electric Car Batteries and Characteristics

1.2.1 Electric Car Batteries

One of the most crucial parts of an automobile system are the batteries for electric vehicles. The only "life" in BEV vehicles is in the batteries. Because the primary source of energy powering a BEV vehicle is electrical energy stored in the battery. Other sources don't exist. The different types of electric car batteries rely on the vehicle's system. Lithium-ion batteries are most frequently utilized in electric vehicles. Batteries with zero emissions are designated as ZEBRA. NiMH batteries are the best option for hybrid electric vehicles. [5]

1.2.2 Types of Electric Car Batteries

Batteries for electric vehicles differ from SLI batteries (starting, lightning and ignition). SLI batteries are typically placed in cars that run on gasoline or diesel. This kind of electric car battery is made to be an energy storage device that can provide power for extended, reliable periods of time.

There are 5 types of electric vehicle batteries :

- Lithium-Ion (Li-On)
- Nickel-Metal Hybrid (NiMH)
- Lead Acid (SLA)

- Ultracapacitor
- ZEBRA (Zero Emissions Batteries Research Activity)

1.2.3 Lithium-Ion (Li-On) Batteries

The Li-On battery is the type of electric car battery that is used the most frequently. We may already be familiar with this battery because it is found in so many portable electronic devices, like laptops and cell phones. The fundamental distinction is one of scale. This is frequently referred to as a traction battery pack because of the larger size and physical capacity it has on electric cars.

The power to weight ratio of lithium-ion batteries is extremely high. High energy efficiency characterizes this kind of electric car battery. High temperature performance is also good. The battery has a higher energy ratio per weight, which is a crucial factor for batteries used in electric vehicles. The car can go farther on a single charge if the battery weight is lower (for a certain kWH capacity).

This battery also has a low "self-discharge" level, so the battery is better than any other battery in maintaining its ability to hold its full charge.

Additionally, Li-on batteries can be recycled, making them the ideal option for individuals who want to drive environmentally friendly electric vehicles. The most lithium batteries are used by PHEVs and BEV vehicles.

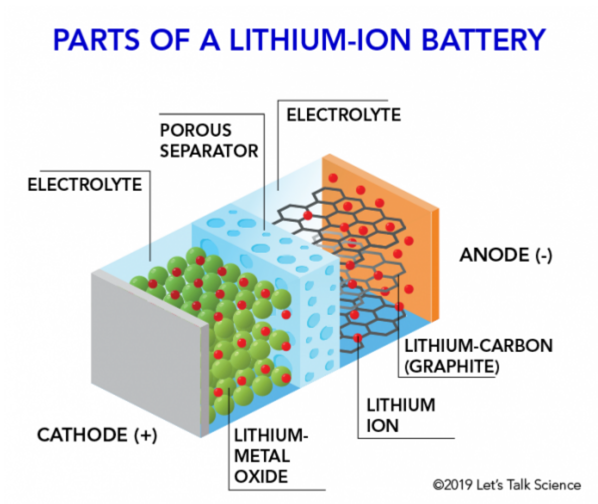

Figure 1.5. Parts of a Lithium-Ion battery [2]

1.2.4 Nickel-Metal Hybrid (NiMH) Batteries

Although some BEV cars have successfully employed NiMH batteries, hybrid electric vehicles (HEV) use them more frequently. This particular hybrid electric vehicle battery does not rely on external power sources (can be recharged from an outside source of the car system). Batteries in hybrid electric vehicles recharge based on engine speed, wheel speed, and regenerative braking.
Compared to SLA or lithium-ion batteries, NiMH batteries have a longer lifespan. NiMH batteries are secure and can withstand improper handling. The following are the main drawbacks of NiMH batteries:

- The price is relatively more expensive
- High self-discharge rate
- Generate significant heat at high temperatures

For electric vehicles whose batteries need to be able to be recharged from outside the system, as from the PLN network, these shortcomings render NiMH less useful as a battery. Due of this, hybrid automobiles use these car batteries the most.

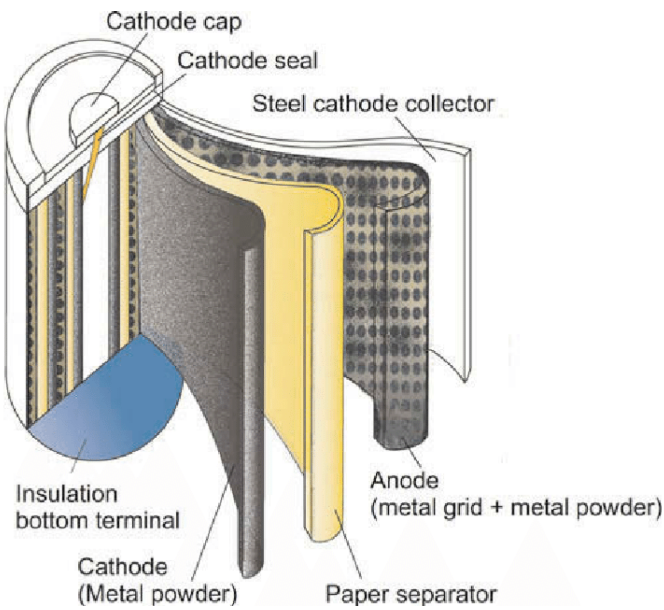

Figure 1.6. Parts of a Nickel-Metal Hybrid battery [2]

1.2.5 Lead Acid (SLA)Batteries

The first rechargeable batteries were SLA (lead-acid) batteries. Lead-acid batteries do lose capacity over time and are significantly heavier than lithium and NiMH batteries, but they are still reasonably inexpensive and secure. Large capacity SLA electric car batteries are being developed, although at the moment SLA batteries are only utilized as a secondary storage system by commercial cars.

Figure 1.7. Lead Acid (SLA) battery [5]

1.2.6 Ultra-capacitor Batteries

The ultra-capacitor battery is not a battery in the conventional sense. This kind of electric vehicle battery really stores polarized liquid between the electrode and the electrolyte, in contrast to other electro-chemical batteries. The liquid's ability to store energy rises along with its surface area. Ultra-capacitor batteries are excellent choices for secondary storage in electric vehicles, just like SLA batteries. This is so that electro-chemical batteries can boost their load levels thanks to the ultra-capacitor. Additionally, ultra-capacitors can give electric vehicles more power when accelerating and using regenerative braking.

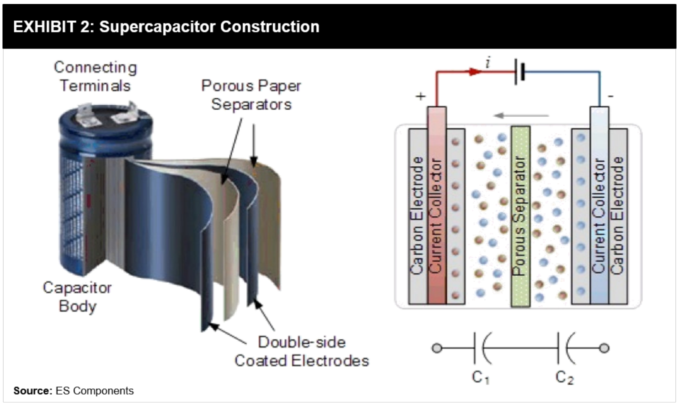

Figure 1.8. Ultracapacitor [5]

1.2.7 ZEBRA Batteries

The ZEBRA electric vehicle battery is a low-temperature sodium-sulfur (NaS) battery that was developed by ZEBRA (formerly "Zeolite Battery Research Africa" before changing its name to "Zero Emissions Batteries Research Activity" battery) in 1985. In fact, ZEBRA batteries were created specifically for use in electric vehicle applications. The battery employs ceramic Na + -beta-alumina electrolyte and NaAlCl4. Characteristics of ZEBRA batteries:

- High power cell so that it fits as an electric car battery
- High temperature batteries operate at more than 270 °C
- The chemical Sodium Nickel Chloride (NaNiCl) provides a nominal operating cell voltage of 2.58 Volts

Advantages of ZEBRA battery

- High energy density (5 times higher than SLA batteries)
- Large cells (up to 500Ah) allow
- Life cycle> 1000 cycles
- Short circuit tolerance
- Safer than Sodium Sulfur cells
- The typical cell failure is shorted but does not cause the battery to fully damage.
- Low cost ingredients

Disadvantages of ZEBRA battery

- Suitable for large capacity batteries (> 20KWh)
- Limited size and capacity range
- Only one factory in the world produces this battery.
- High internal resistance
- Liquid sodium electrode
- High operating temperature.
- Preheating is required to get the battery up to an operating temperature of 270 ° C (up to 24 hours from cold conditions)
- Uses 14% of its own capacity per day to maintain temperature when not in use.
- Thermal management is required

Figure 1.9. ZEBRA Batteries [3]

1.3 Charging Modes in IEC 61851

The International Electrotechnical Commission (IEC) defines charging in 4 modes in IEC 61851-1 [4, 8].

1.3.1 Mode 1: Slow charging from a regular electrical socket (single- or three-phase)

Through normal socket-outlets found in homes, the car is connected to the electrical grid, depending on the nation, generally ranked at around 10 A. Mode 1 requires that the electrical installation adhere to safety regulations. rules and is required to have an earthing system, an overload circuit breaker, and an earth leaking protection. In order to avoid unintentional connections, the sockets contain blanking mechanisms. The first restriction is the power that is available, to prevent the dangers of:

- Heating of the plug and cables after prolonged, intensive use at or close to the maximum power (which varies by nation from 8 to 16 A).
- If the electrical installation is outdated or certain protection measures are missing, there is a risk of fire or electric injuries.
- Because there is no dedicated circuit for the charging socket and it shares a switchboard feeder with other sockets, the charging will cease if the total consumption exceeds the protection limit, which is typically 16 A.

For the sake of safety and service quality, all these variables put a cap on the power in mode 1. The value of 10 A seems to be the ideal middle ground at this time as the limit is still being determined. The EV is connected directly and passively to the AC mains at a maximum current of 16 A at 250 V for a single phase or 480 V for a three-phase connection that includes the earth. Extra control pins are not present on the connection. The EVSE must deliver earth to the EV (as described above) and include ground fault protection for electrical protection. Mode 1 charging is not permitted in various nations, including the United States. One issue is that not all household installations have the necessary earthing. For this, mode 2 was created as a workaround.

Figure 1.10. Mode 1 charging [8]

1.3.2 Mode 2: Slow charging from a regular socket but with some EV specific protection arrangement

A domestic outlet connects the car to the main electrical grid. A single-phase or three-phase network with an earthing connection installed is used for charging. The cable has a protective mechanism built in. Since the connection is more specialized, this approach costs more than Mode 1.
The EV is connected directly and semi-actively to the AC mains at a maximum current of 32 A at 250 V for a single phase or 480 V for a three-phase system that includes the earth. The EV supply equipment (EVSE), which must be a part of or located within 0.3 meters (1.0 ft) of the AC mains socket, has a direct, passive connection

to the AC mains. From the EVSE to the EV, however, there is an active connection with the addition of the control pilot to the passive components. Depending on the presence of a vehicle and the demand for charging electricity, the EVSE offers functional switching, ground fault, over-current, and over-temperature protection. A SPR-PRCD that complies with IEC 62335 Circuit breakers - Switched protected earth portable residual current devices for class I and battery powered vehicle applications must be used to provide some protections. An IEC 60309 connector with a 32 A rating is used in one such example. The interaction between the EV and the EVSE, which is located incable, shows that 32 A can be drawn.

Figure 1.11. Mode 2 charging [8]

1.3.3 Mode 3: Slow or fast charging using a specific EV multi-pin socket with control and protection functions

The car is directly wired into the electrical system using a particular plug and socket as well as a separate circuit. Additionally, the installation has a permanent control and protection function (on the wall). The only charging mode that complies with the rules governing electrical installations is this one. Additionally, it enables load shedding, which reduces the amount of time it takes for an electric vehicle to charge while still allowing domestic appliances to run.
This is an active connection of the EV to a fixed EVSE, which can be either 250 V 1-phase or 480 V 3-phase including earth and control pilot; either with a compulsorily captive cable with extra conductors, at a maximum current of 250 A, or in a way that is compatible with mode 2, with an optionally captive cable, at a maximum current of 32 A. The charging supply must be properly communicated with via the control pilot in order to be made operational by default. The communication link between the electronics in cars and the charging station enables smart grid integration.

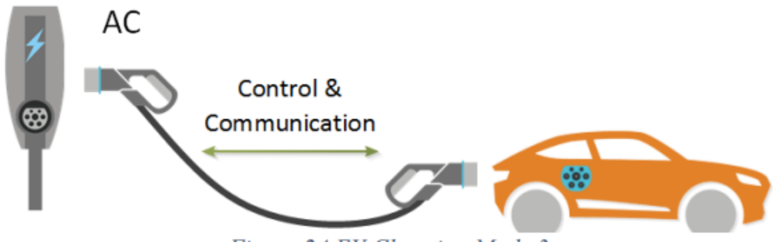

Figure 1.12. Mode 3 charging [8]

1.3.4 Mode 4: Fast charging using some special charger technology such as CHAdeMO

Through an external charger, the electric car is connected to the main power grid. The vehicle charging cable, control and protection features, and the installation are all permanently placed. This is an active connection of the EV to a fixed EVSE with a maximum current of 400 A and a 600 V DC voltage that includes the earth and control pilot. The EVSE is more expensive than a mode 3 EVSE since the DC charging power is rectified from AC mains power in the EVSE.

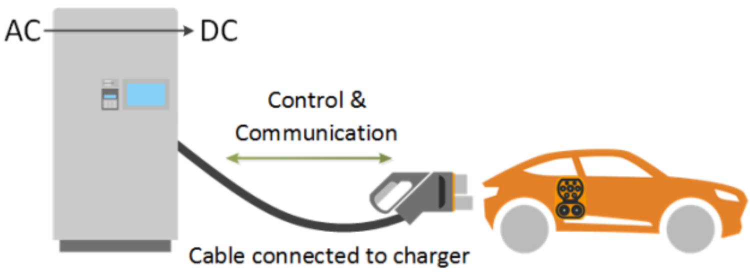

Figure 1.13. Mode 4 charging [8]

Mode	Limits			Supply	Applications	Notes
	Phases	Current	Voltage			
1	1-Ph	16A	250V	AC	electric bikes & scooters	Direct connection of vehicle to conventional electrical outlets is not allowed in the US, Israel, and England; prohibited for public charging by Italy; restricted in Switzerland, Denmark, Norway, and Germany.
	3-Ph	16A	480V			
2	1-Ph	32A	250V	AC	Slow AC	Requires control box between vehicle and electrical outlet. Prohibited for public charging by Italy; restricted in US, Canada, Switzerland, Denmark, France, and Norway.
	3-Ph	32A	480V			
3	1-Ph	ND	250V	AC	Slow and Quick AC	EVSE permanently connected to electrical grid. Typical public charger installation
	3-Ph	ND	480V			
4	-	ND	ND	DC	Fast Charging	Current conversion handled by EVSE, not EV.

Figure 1.14. Battery charging modes comparison [8]

1.4 Plug types

1.4.1 Type 1 (AC Type 1)

SAE J1772 (IEC 62196 Type 1), also known as a J plug, is a North American standard for electrical connectors for electric vehicles maintained by the SAE International.

Figure 1.15. Type 1 plug [8]

1.4.2 Type 2 (AC Type 2)

In January 2013, the IEC 62196 Type 2 connector was selected by the European Commission as official charging plug within the European Union.It has since been adopted as the recommended connector in some countries outside of Europe, including New Zealand. While the connector type 2 is for charging battery electric vehicles at 3–50 kilowatts, with a plug modified by Tesla capable of outputting 150 kilowatts.

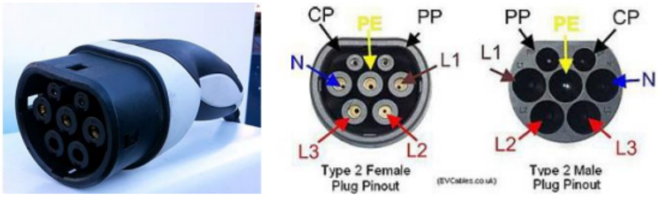

Figure 1.16. Type 2 plug [8]

1.4.3 Combined Charging System (CCS)

Two additional connectors are added to Type 1 or Type 2 vehicle inlets and charging plugs for Combined Charging System (CCS) DC charging in order to connect high voltage DC charging stations to the car's battery. These connectors are also sometimes referred to as Combo 1 or Combo 2. According to the country of interest, the choice of Combo 1 or Combo 2 type inlets is typically standardized, preventing public charging providers from having to install cables with both variants. The majority of the rest of the world uses Combo 2 style vehicle inlets for CCS, while North America typically uses Combo 1 style vehicle inlets.

Figure 1.17. Type 1 & 2 CCS plug [8]

1.5 Advantages and Disadvantages of Electric Vehicles

Advantages

[2, 6, 13]

- No Gas Required: Electric cars are entirely charged by the electricity you provide, meaning you don‘t need to buy any gas ever again. Driving fuel based cars can burn a hole in your pocket as prices of fuel have gone all time high. With electric cars, this cost can be avoided as an average American spends $2000-4000$ on gas each year. Though electricity isn‘t free, an electric car is far cheaper to run.
- No Emissions: Electric cars are 100 percent ecofriendly as they run on electrically powered engines. It does not 57 emit toxic gases or smoke in the environment as it runs on clean energy source. You‘ll be contributing to a healthy and green climate.
- Safe to Drive: Electric cars undergo same fitness and testing procedures test as other fuel powered cars. In case an accident occurs, one can expect airbags to open up and electricity supply to cut from battery. This can prevent you and other passengers in the car from serious injuries.
- Cost Effective: Earlier, owing an electric car would cost a bomb. But with more technological advancements, both cost and maintenance have gone down. The mass production of batteries and available tax incentives have further brought down the cost, thus, making it much more cost effective.
- Low Maintenance: Electric cars runs on electrically powered engines and hence there is no need to lubricate the engines. Other expensive engine work is a thing of past. Therefore, the maintenance cost of these cars has come down. You don‘t need to send it to service station often as you do a normal gasoline powered car.
- Reduced Noise Pollution: Electric motors are capable of providing smooth drive with higher acceleration over longer distances.

Disadvantages

[2, 6, 13]

- Recharge Points: Electric fueling stations are still in the development stages. Not a lot of places you go to on a daily basis will have electric fueling stations for your vehicle, meaning that if you‘re on a long trip and run out of a charge, you may be stuck where you are.

- Electricity isn‘t Free: Electric cars can also be a hassle on your energy bill if you‘re not considering the options carefully. Sometimes electric cars require a huge charge in order to function properly – which may reflect poorly on your electricity bill each month.

- Short Driving Range and Speed: Electric cars are limited by range and speed. Most of these cars have range about 50-100 miles and need to be recharged again. You just can‘t use them for long journeys as of now, although it is expected to improve in the future.

- Longer Recharge Time: While it takes couple of minutes to fuel your gasoline powered car, an electric car takes about 4-6 hours to get fully charged. Therefore, you need dedicated power stations as the time taken to recharge them is quite long.

- Normally 2 Seaters: Most of the electric cars available today are small and 2 seated only. They are not meant for entire family and a third person can make journey for other two passengers bit uncomfortable.

- Battery Replacement: Depending on the type and usage of battery, batteries of almost all electric cars are required to be changed every 3-10 years [2].

- Not Suitable for Cities Facing Shortage of Power: As electric cars need power to charge up, cities already facing acute power shortage are not suitable for electric cars. The consumption of more power would hamper their daily power needs.

- Some base models of electric cars are still very expensive because of how new they are and the technology it took to develop them. Thus, as in any reality, there are two sides. So far, this industry is only developing, especially in our country. There is still a shortage of opportunities for most people to have such a car. But technologies are developing rapidly, and we hope that in the very near future this technology will bring us much benefit.

CHAPTER 2

V2G Function

2.1 V2G Technology

The term "vehicle-to-grid" (V2G) refers to a system in which plug-in electric vehicles (EVs), such as battery electric vehicles (BEV) or plug-in hybrid vehicles (PHEV), interact with the power grid to sell demand response services by either resupplying electricity to the grid or by throttling their charging rate.
EVs with V2G storage capacity may be able to store and release electricity produced by intermittent renewable energy sources, such as solar and wind, whose output varies with the weather and the time of day.

2.2 Benefits of V2G

In order to optimize the supply of local renewable energy and lower infrastructure costs, V2G directs the charging and discharging of EV batteries based on user needs and the grid's electricity supply. Meanwhile, EV owners can benefit from greener, more cost-effective electricity consumption while also earning money for supporting the grid.
Accordingly, V2G offers the following advantages to EV owners and the distribution system:

- Supporting electrical grid, reducing concerns for grid overload
- Maximise the business case opportunity of your EVs
- Cheap and fast energy storage
- Making use of existing resources
- Reduction of environmental impact

2.3 How V2G works

According to user requirements and the amount of electricity that is currently available on the grid, V2G controls how electric car batteries are charged and discharged.

When there is a surplus of electricity (for example, during the peak of renewable energy production), charging happens at its highest rate. However, when there is a surplus of electricity, vehicles can contribute to the grid.

2.4 Challenges of V2G

Due to the high number of charge/discharge cycles, battery degradation is the only technical drawback of V2G operation. With a few exceptions, the majority of electric car manufacturers do not offer warranties for V2G operations. To be applied on a broad basis, this method is still in its early phases.

2.5 Applications for V2G

Apart from providing local services at individual levels, when aggregated, EVs can also provide services to the grid for:

- Voltage regulation
- Frequency regulation

The cost of energy consumption for end users will be kept to a minimum, and there will be less of an impact on the electric power system, thanks to the best possible use of the energy resources (battery reserves for electric vehicles).

In addition to V2G, it is important to include V2X, which can be vehicle-to-building, vehicle-to-vehicle, or vehicle-to-home. Different applications nevertheless use the same principle.

2.6 V2G Architecture

The electricity grid, the ISO, the aggregator, and the PEVs are the system's primary components. We also assume that N is sufficiently large (on the order of hundreds of vehicles) to offer the capacity and electricity necessary for frequency regulation. N is the number of PEVs affiliated with an aggregator that are prepared to provide regulation in real time throughout the compromised period. If the power grid requires frequency regulation, the ISO notifies the aggregators to seek V2G regulation and uses their bids to calculate the market price for frequency control. According to its representation below[2.1], two-way wired or wireless communications are formed to connect the aggregators, ISO, electricity grid, and PEVs.

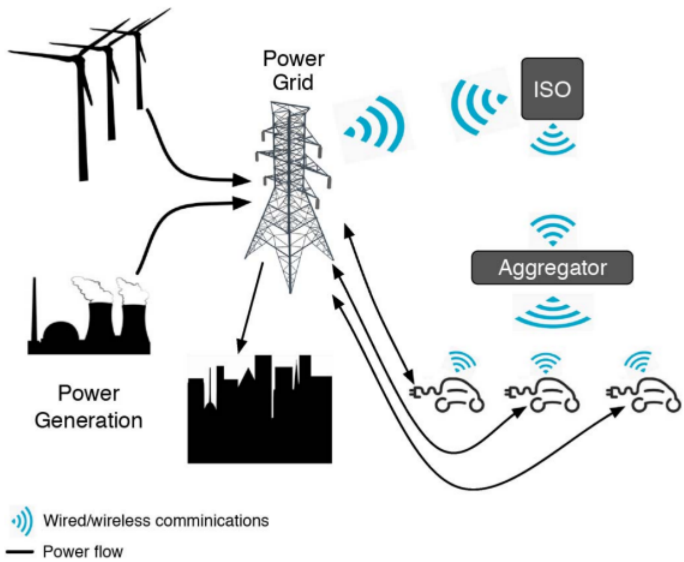

Figure 2.1. Power system model [10]

CHAPTER 3

Cretan Power System

3.1 Crete Electricity Grid

With a surface area of around 8500 km2, Crete is the largest Greek island and the fifth-largest in the Mediterranean Sea. During the summer, its population triples. Moreover, it is Greece's largest isolated system. Additionally, from 2000 to 2008, there was a noticeable annual growth in electricity demand of up to 7%. As a result, 2.8TWh of energy were consumed annually in 2008 as opposed to a more modest 280GWh in 1975. However, from 2008 to 2011, the amount of power consumed stayed constant between 2.8 and 2.65TWh. The primary basis of the electricity generation system is oil-fired thermal power plants. Steam turbines, diesel generators, gas turbines, and one combined cycle unit are just a few of the conventional units that have been erected in three power plants with a combined capacity of 813MW, as shown in Table 3.1 [1, 4].

Power Station	Steam	Diesel	Gas	CC	Total
Linoperamata	106	44	115	-	265
Chania	0	0	216	132	348
Atherinolakos	102	98	-	-	200
Total Capacity	208	142	331	132	813

Table 3.1. Installed capacity (in MW) per unit type and power stations

The base-load is mostly supplied by the steam and diesel units. In outage situations, the gas turbines typically handle the daily peak load or any additional load that cannot be met by the other units. The average cost of the electricity being delivered is greatly raised by these units' high operating expenses. Figure 2 shows a diagram of the Cretan power system, which shows the major power plants and the 150kV transmission network.

3.2 RES in Crete

On the island, the average wind speed is frequently higher than 8.5m/sec. Additionally, Crete has one of Europe's highest solar potentials. Crete is the perfect location for the installation of wind and solar technology because of these features. As a result, there are around 20 wind farms with a combined rated output of 183 MW, with half of them located in the Sitia region on the island's eastern side. A total of 94MW has been built via the addition of more than 1000 small PV parks, the majority of which are 80kW apiece, and 1800 roof PVs (July 2013). . It should be also noted that since 2000, Crete steadily meets more than 10% of the demand by RES.
Also, it is worth to mention that there is an interconnection plan between the Cretan power system and the main Greek power system, as well as an interconnection plan between Crete, Cyprus and Israel. Should these plans implemented, the renewable energy penetration in the island is expected to be increased significantly (already there are 1000MW of authorized wind parks) and may make Crete an exporter of RES electricity.

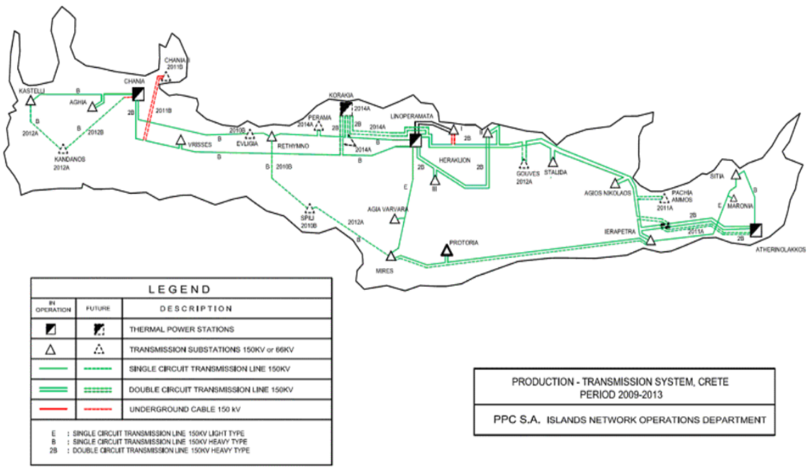

Figure 3.1. Cretan power system map [12]

Part II

Experimental Analysis

CHAPTER 4

Explaining the Algorithm

Firstly a transportation model must be established in order to calculate the daily load of the EVs in Crete. The model used resembles a typical day of travelling (e.g. traveling for work or for social interactions).

4.1 Brief Presentation of the Algorithm

The Algorithm begins by creating a model of the daily schedule for every EV in every county of Crete. In Matlab a routine was created, in order to find the daily schedule for every car and extract an overall charging profile. The logic used to create the daily schedule for every EV is the following;

1. Choose a random vehicle type from the available ones
2. The EV starts from the house
3. The next destination will be decided based on the time of departure
4. The duration of travel gets randomly selected from a distribution
5. The velocity of the vehicle also gets randomly selected from a distribution and then the distance is calculated using the travel duration
6. Depending on the location, the duration the vehicle is parked gets randomly chosen from a distribution
7. The departure time for the next destination is being calculated using the duration the vehicle is parked
8. The battery percentage is calculated, using the distance travelled and the consumption of this EV

9. Acoording to the battery percentage is is decided whether the EV will charge or not, and the power needed to charge is calculated. If the EV won't charge it starts the next travel with the same battery level.

10. The procedure will be repeated until 24 hours have passed

4.2 Data and Variables

All the varaibles used are being presented below and they will be analysed individually.

- city
- $EV.SoC_0$
- type
- EV.Consumption
- $EV.SoC_{max}$
- $EV.SoC_{min}$
- $EV.P_{max}$
- $EV.P_{min}$
- SoC_{target}
- bat_kwh
- destination
- depart
- travelTime
- arrivalTime
- velocity
- dsTravelled
- parked
- realConsumption
- P

city

The total number of EVs was distributed between the four counties in Crete. More speficically, the vehicles were distributed according to the population in every county, so Chania has 25.17%, Heraklion 49%, Rethymno 13.73% and Lasithi 12.1% of the total EV fleet.

$EV.SoC_0$

This is the battery percentage in wich the vehicle will start its first trip of the day. The percentage is chosen randomly from a random distribution [4.1] which sets this value between 75% and 100%.

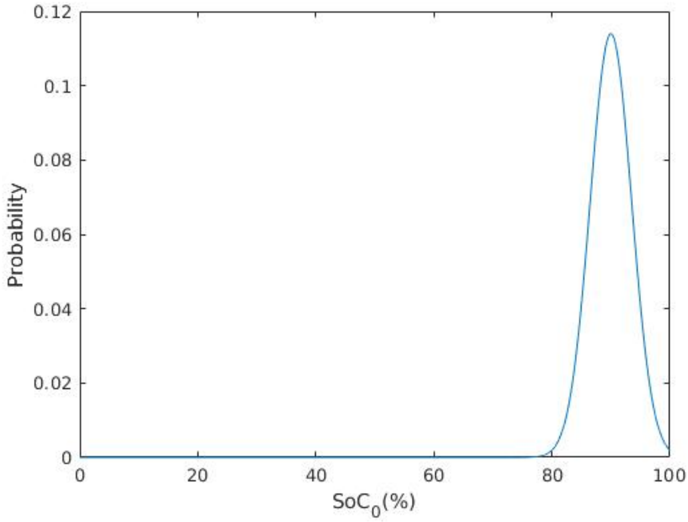

Figure 4.1. Distribution of the original battery percentage

type

Four types of EVs were selected [4.1] [4] with differences regarding the Consumption, the battery capacity and the Power. The vehicle type is chosen randomly by picking a number from 1 to 4 for every vehicle. On the table below we can see the characteristics of every EV type. It is noteworhty that in order to simulate the real world use of the EVs, their consuption is being inflated by 30%. This happens due to uncontrollable factors, such as the climate and the driving style of each owner.

Type	Battery Capacity(kWh)	Pmax(kW)	Consumption(kWh/km)
1	17.6	4.6	159
2	16	3.7	161
3	35	11	156
4	36.8	7.2	162

Table 4.1. EV types and their characteristics

$EV.Consumption$

This is the consumption ($\frac{KWh}{km}$) of the EV accordingto the manufacturer of the vehicle and differs depending on the vehicle type.

$EV.SoC_{max}$

This term reffers to the maximum capacity of the vehicle's battery(KWh) and also differs depending on the vehicle type.

$EV.SoC_{min}$

The minimum battery capacity(KWh) of the vehicle in order not to damage the battery. It is expressed as:

$$EV.SoC_{min} = 0.2 \times EV.SoC_{max} \tag{4.1}$$

$EV.P_{max}$

The maximum power(kW) the vehicles draws from the grid while charging. This also differs depending on the vehicle type.

$EV.P_{min}$

The maximum power(kW) the vehicle discharges, giving power back to the grid.

SoC_{target}

The battery capacity(kWh) until which the EV will charge when connected to the grid. Randomly gets assigned a value between 75% and 98% of $EV.SoC_{max}$.

$$0.75 \times EV.SoC_{max} \geq SoC_{target} \leq 0.98 \times EV.SoC_{max} \tag{4.2}$$

bat_kwh

The energy stored in the battery of the EV at any given time. When the vehicle departs from home it is:

$$bat\_kwh = EV.SoC_0 \ (kWh) \tag{4.3}$$

When the vehicle charges it is:

$$bat\_kwh = EV.SoC_{target} \ (kWh). \tag{4.4}$$

In case the vehicle does not charge it stays the same. Finally during travel it is reduced due to the consumption of the EV as shown here:

$$bat\_kw = bat\_kw - realConsumption \ (kWh) \tag{4.5}$$

destination

The Figure 4.2 shows the distribution for the departure rate of the EVs, that is derived from real-world data in Greece. By adding and normalizing every rate individually, Figure 4.3 is created from which the algorithm chooses randomly the next destination for every trip of the vehicle. Moreover a random number between 1 and 0 is generated and depending on the time of dearture for this specific trip, a destination is choosen, depending on the relative position of the point to the curves. For example let the random number be 0.7 and the trip begins at 20:00. then the next destination will be 'home'. Lastly the possible destinations are 'work', 'home' and 'shop/social'.

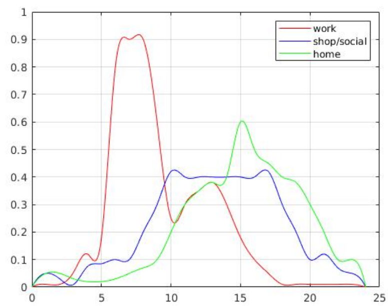

Figure 4.2. Distribution of the departure rate

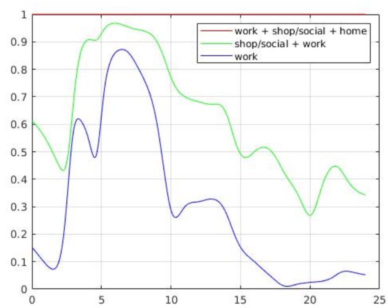

Figure 4.3. Choosing the next destination

depart

This varable represents the time of departure for the new trip. It is randomly selected in the begining from a distribution as shown on Figure 4.4. This distribution is created, taking into consideration that most of the population starts from home every day aroun 8:00. Every other departure time is calculated as shown here:

$$depart = arrivalTime + parked \tag{4.6}$$

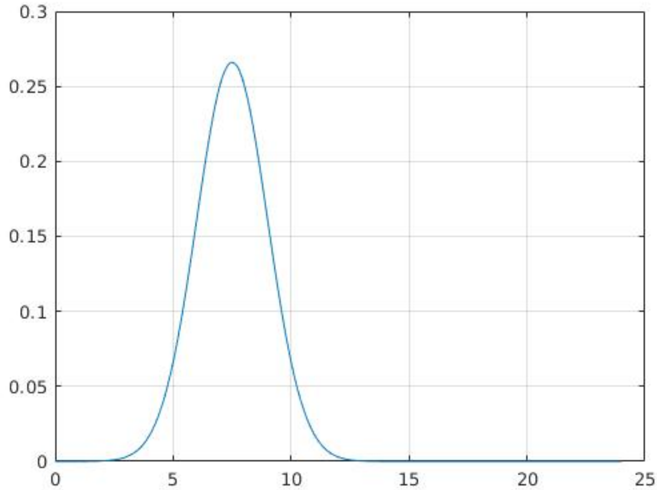

Figure 4.4. Distribution for the first departure time of the vehicle

travelTime

A Normal distributionwas created for every county in Crete in order to find the duration of every trip. The creation of every distribution was based on the avarage distances in every county. So as seen below [4.5] the duration for every trip in Heraklion is betwwen 5 and 38 minutes, in Chania between 4 and 28 minutes, in Rethymno between 5 and 25 minutes and in Lasithi between 2 and 18 minutes.

arrivalTime

The time of arrival for each vehicle in every new location is given by:

$$arrivalTime = \frac{travelTime}{60} + depart\ (h) \tag{4.7}$$

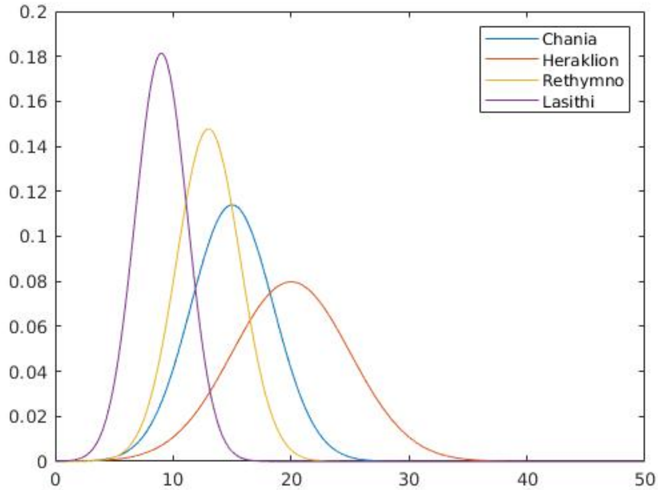

Figure 4.5. Distributions for the duration of each trip

velocity

A random value is select from a normal distribution, derived from actual data that a vehicle is traveling in the city with a speed between 10 and 58 km/h.The value selected is the vehicle's effective velocity. The aforementioned distribution is shown in figure [4.6].

dsTravelled

The distance travelled by the EV in every trip and is given by :

$$dsTravelled = velocity \times travelTime \tag{4.8}$$

parked

The time the vehicle stays parked between two trips. As seen below [4.7] a distribution was created for every type of travel. Both 'work' and 'home' are normal distributions. On the other hand the distribution for 'shop/social' was created from random data, due to it's nature.

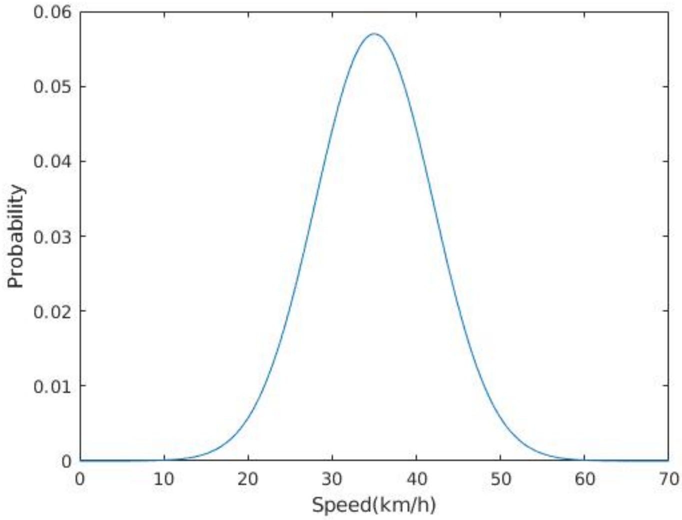

Figure 4.6. Distribution for the effective velocity of the vehicle

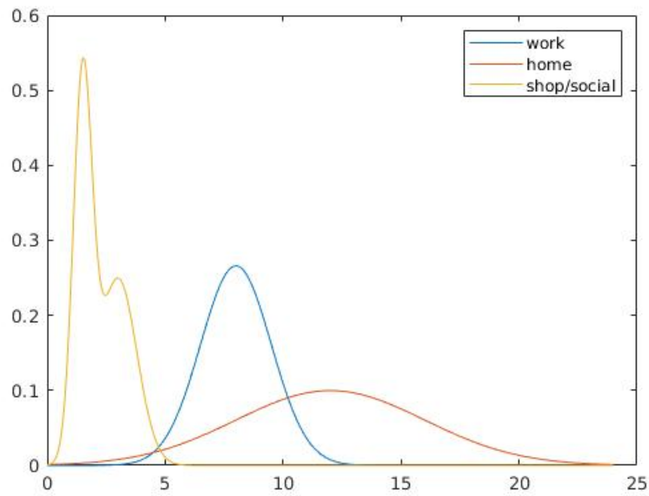

Figure 4.7. Distributions for the time parked in each destination

$realConsumption$

This term reffers to the consumtion of electrical energy for every EV, in every trip. It is given by :

$$realConsumption = EV.Consumption \times dsTravelled\ (kWh) \tag{4.9}$$

P

This is the power used when the vehicle is charging.

Dumb Charging is given by:

$$P_{dumb}(kW) = \begin{cases} EV.P_{max} & , P_{dumb} > EV.P_{max} \\ \frac{SoC_{target} - bat\_khw}{parked} & , elsewhere \end{cases} \tag{4.10}$$

Smart Charging The following series of equations are being used:

$$net\ load(t) = Crete\ load(t) - P_{RES}(t) \tag{4.11}$$

$$d1(t) = \frac{max(net\ load(t)) - net\ load(t)}{max(net\ load(t))} \tag{4.12}$$

$$d(t) = \frac{d1(t)}{mean(d1(t))} \tag{4.13}$$

Then d is shifted around 0 in order for the vehicle to give power back to the grid (V2G) and the absolute values of the negative instances are being added to the positive instances, so the total sum will be preserved. Finally:

$$P_{smart}(t) = d(t) \times P_{dumb}\ (kW) \tag{4.14}$$

Where $Crete\ load$ is the real load of Crete and P_{RES} the energy produced from RES in a random day.

4.3 Analysis of the Daily scedule Algorithm

In this section the estimation of the daily schedule of the EVs is analysed. In order to be easier to comprehend, a random vehicle in Rethymno was selected and a two-day schedule was created. Below in figure 4.8 a graph of a two-day EV schedule is presented followed by the analysis of how it was calculated. Note that every vehicle starts from Home.

At fisrt the type of the EV is chosen by a random number from 1-4. This defines the following characteristicsof the vehicle :

1. $EV.SoC_{max}$
2. $EV.SoC_{min}$
3. $EV.P_{max}$
4. $EV.P_{min}$

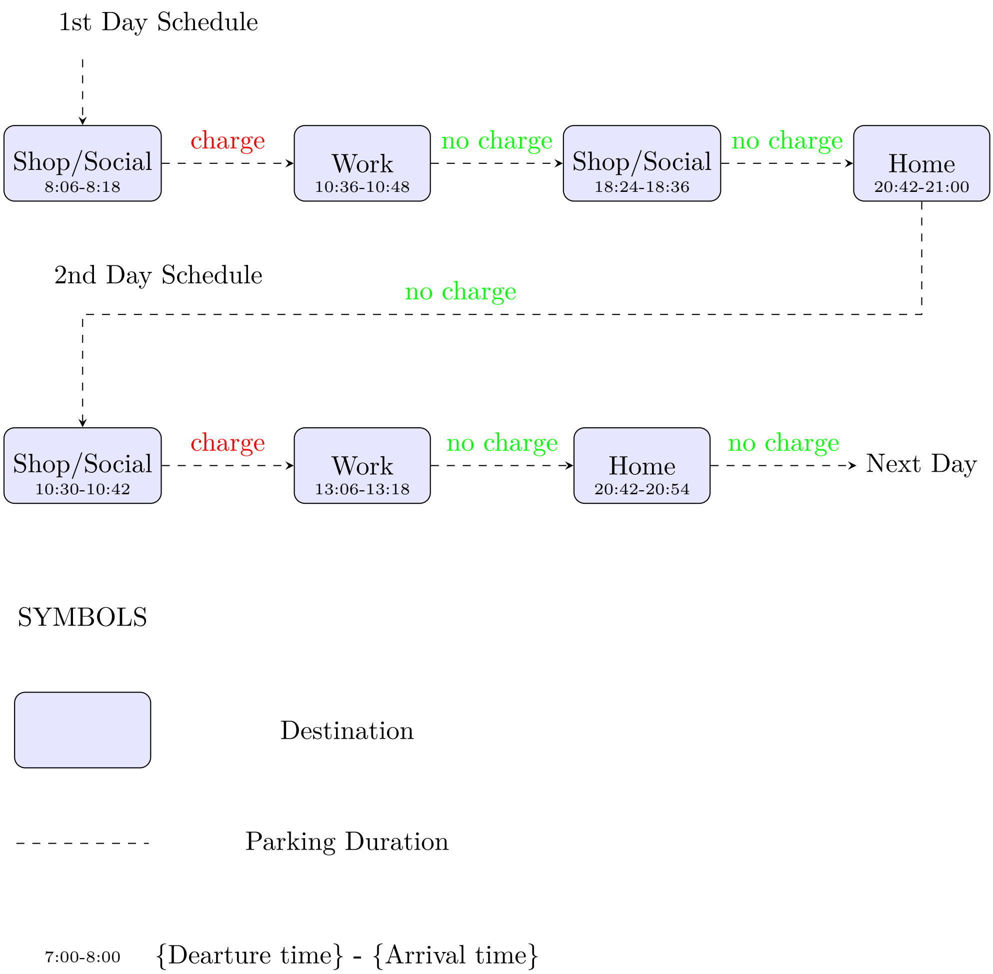

Figure 4.8. Two-day schedule of a random EV

5. *EV.Consumption*

After that, acording to the distributions in figures 4.1, 4.4 the variables $EV.SoC_0$ and *depart* are initialized accordingly. Based on the distribution, the vehicle start its jurney from Home at 8:06 and according to figure 4.5 the duration of the trip is dictated based on the county, which in our case is 12 minutes.

Next the type of the trip is decided, in this case Shop/Social, using the following steps: a random number between 0-1 is generated and based on the departure time of the trip, the destination is selected depending on the where the point is on the curve in figure 4.3. In any case the destination is different from the starting location, in our case Home.

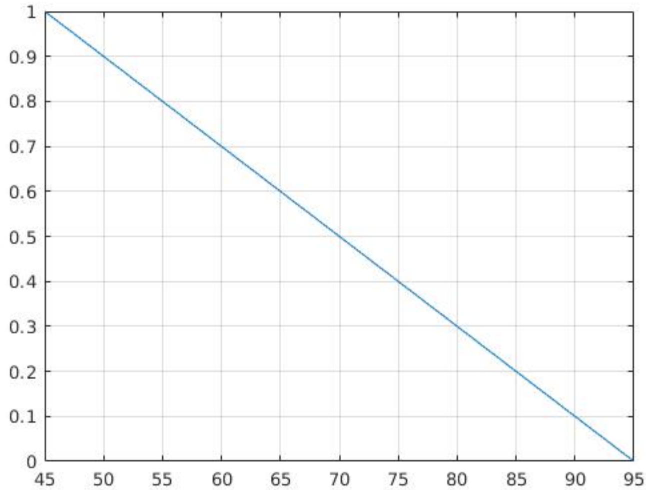

Figure 4.9. Distributions for the time parked in each destination

Then the arrival time at the destination 8:18 is calculated using [4.7], the *velocity* is randomly selected using figure 4.6 followed by the distance the vehicle travelled using [4.8]. Its consumption is then calculated with [4.9], in order to find the battery capacity as per [4.5]. The time the vehicle is parked 2h18m, based on the location, is assigned using the distribution in figure 4.7 and finally it is decided whether the EV will charge or not.

Specifically the battery percentage is calculated $bat\_percentage = \frac{bat\_kw}{EV.SoC_{max}} \times 100\%$ and if it is greater than 95% the vehicle won't charge, in case it is less than 45% the vehicle will charge. In any other case a random number between 0-1 is generated and based on the point in the curve shown in figure 4.9 it is decided whether the EV will charge or not. In case the vehicle does not charge the variable *bat_kw* stays the same.

Moreover, when the vehicle charges, the variable SoC_{target} is assigned a value between 75%-98% of the SoC_{max}. If the time is sufficient the vehicle will charge up to the SoC_{target} as described in [4.4], otherwise the vehicle will charge with $EV.P_{max}$ until it is disconnected from the grid. Finally the new departure time is calculated [4.6] and the routine is repeated until 48 hours have passed. A two-day schedule is created at this point and the system is stable.

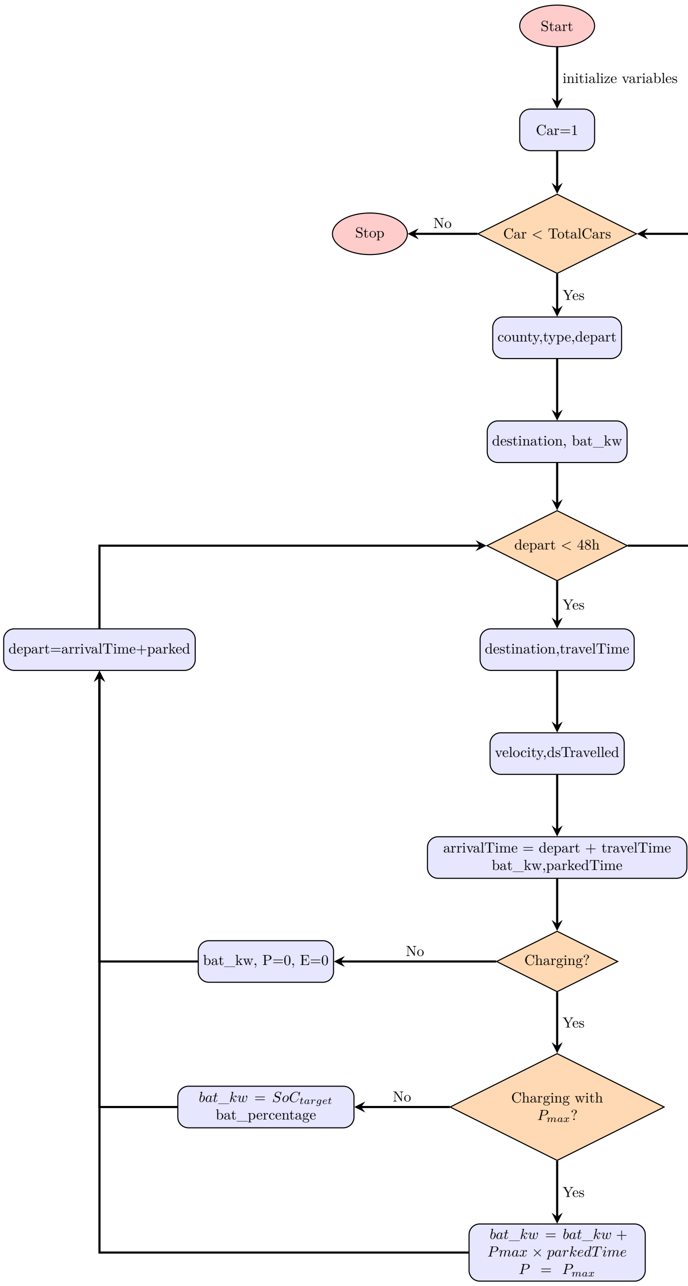

Figure 4.10. Flowchart of the two-day schedule algorithm

4.4 Charging Strategies

Non-Controlled/Dumb Charging

It is the simplest form of charging and is used when deemed necessary. The vehicle absorbs a stable amount of Power during the whole process of charging. The starting time as well as the duration in which the vehicle charges are dictated by the characteristics of each vehicle and each trip. Non-Controlled charging in correlation with a high enough EV penetration percentage, significantly impacts the peak of the total load on the grid in a negative way.

Vehicle Based Smart/Optimal Charging

This method aims to help the system and minimise the consequences of the RES, so it takes into consideration the net load of the grid, which translates to the real load in coordination with the energy produced by RES. The balance of the system is based on the cooperation of the EVs and RES. The charging aims to use mostly green energy produced by RES(such as wind and solar) when it is plenty. The produced energy of the RES is not stored anywhere, but is used in whole.
Two methods are being used to combat major fluctuation in the power demand:

- **Peak shaving**: lowering the demand on high demand periods.
- **Valley filling**: increase the load on low demand periods.

An indicative example of a vehicle follows:

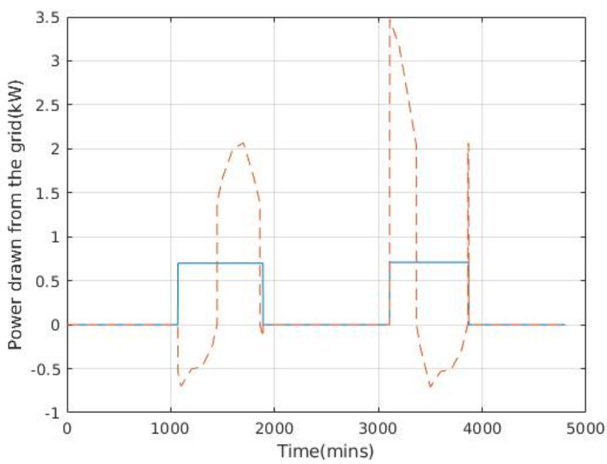

Figure 4.11. An example profile for Smart/Optimal charging

Aggregator Controlled Charging

The aim of this charging method is to help the system and minimise the consequences of the RES. It takes into consideration the net load of Crete and tries to minimise the use of traditional non-renewable energy sources and any fluctuation on the demand in power. This is achieved by forecasting the RES produced energy and minimise the demand of power when the produced energy is the lowest.

It is worth mentioning that both **Vehicle Based Smart/Optimal Charging** and **Aggregator Controlled Charging** methods use the V2G technology. Their main difference is that the first one is done on a vehicle basis and the second one is done by the Aggregator, with further benefits discussed bellow.

4.5 Battery Model

In addition to the day-schedule algorith, the dynamic boundries for the EV batteries are estimated during the 2-day period, as shown on figures 4.12 and 4.13. In the first case we can see that the vehicle charges with power les than P_{max}, has plenty of time to discharge its battery until it reaches SoC_{min} and is able to charge to SoC_{target}. In the second case we can see that the time at the charging station is not enough and the vehicle charges with P_{max}, while it is unable to reach the SoC_{target} In the third case we can see that the time is not sufficient to discharge the battery in order to reach the SoC_{min}. Consequently in the first and third case, the times $t_{l1}, t_{l2}, t_{h1}, t_{h2}$ are calculated, followed by the dynamic boundies SoC_{low} and SoC_{high} according to the equations 4.15 - 4.20 [9, 11]. Moreover the energy stored in the batteries during arrival and departure is being stored. Those energies are being sumed for all the vehicles in order to calculate the energy needed by all the vehicles in Crete in any given moment. This will be further analysed in the next subsection.

$$SoC_{low}(i,t) = \begin{cases} SoC_{min}(i) + P_{min}(i) \times (t - t_{l1}(i)) & , t < t_{l1}(i) \\ SoC_{min}(i) & , t_{l1}(i) \leq t \leq t_{l2}(i) \\ SoC_{min} + P_{max}(i) \times (t - t_{l2}(i)) & , t < t_{l2}(i) \end{cases} \tag{4.15}$$

$$SoC_{high}(i,t) = \begin{cases} SoC_{max}(i) + P_{max}(i) \times (t - t_{h1}(i)) & , t < t_{h1}(i) \\ SoC_{max}(i) & , t_{l1}(i) \leq t \leq t_{h2}(i) \\ SoC_{max} + P_{min}(i) \times (t - t_{h2}(i)) & , t < t_{h2}(i) \end{cases} \tag{4.16}$$

$$t_{l1}(i) = t_0(i) - \frac{SoC_0(i) - SoC_{min}(i)}{P_{min}(i)} \tag{4.17}$$

$$t_{h1}(i) = t_0(i) - \frac{SoC_0(i) - SoC_{max}(i)}{P_{max}(i)} \tag{4.18}$$

$$t_{l2}(i) = t_f(i) - \frac{SoC_{target}(i) - DSoC_{target}(i) - SoC_{min}(i)}{P_{max}(i)} \tag{4.19}$$

$$t_{h2}(i) = t_f(i) - \frac{SoC_{target}(i) + DSoC_{target}(i) - SoC_{max}(i)}{P_{min}(i)} \tag{4.20}$$

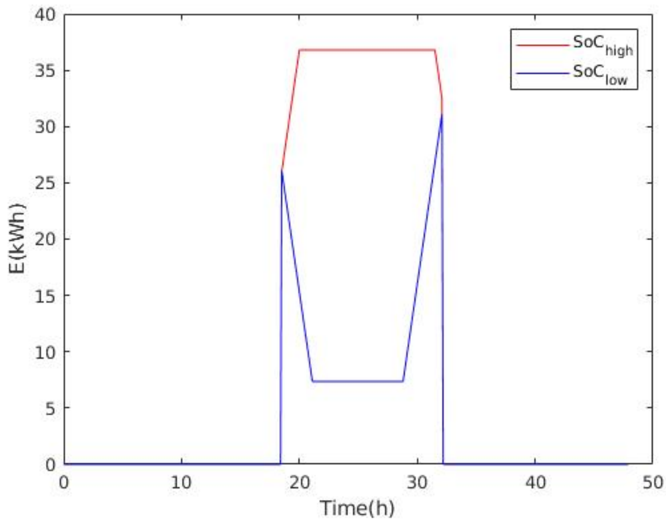

Figure 4.12. An example of dynamic boundries for a vehicle in 48 hours.

4.6 Aggregator Model

The V2G function uses the stored energy in the batteries of the EVs and the administrator of charging and discharging of the batteries, called Aggregator and is a new player(source) in the electricity market. Due to the large volume of EVs studied here, a dynamic battery was used. This battery represents the Aggregated Energy stored in all the vehicles that are parked at a given moment in the day. The power neede to charge and discharge this battery is equal to the sum of the power needed to charge and discharge, accordingly, every car connected to the grid a a given moment. Noted that the number of connected vehicles to the grid changes every t, since vehicles connect and disconnect at any given moment. In order to calculate the dynamic boundries of this dynamic battery, firstly $DSoC$ mfor the whole 24 hours must be calculated. $DSoC$ is equal to the total amount of energy of the vehicles that depart

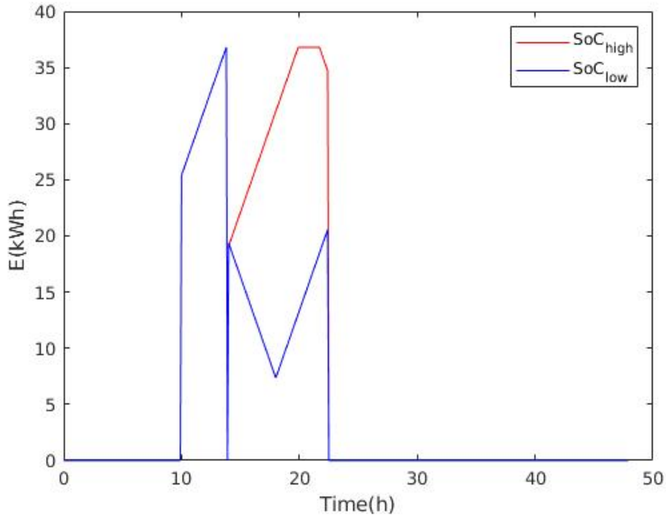

Figure 4.13. An example of dynamic boundries for a vehicle in 48 hours.

minus the energy of those that arrive, in every t. That means that $DSoC$ for every t is calculated as follows:

$$SoC_{arr}^{total}(t) = \sum_{i=1}^{n_{arr}(t)} SoC_{arr}(i,t), \forall t \tag{4.21}$$

$$SoC_{dep}^{total}(t) = \sum_{i=1}^{n_{dep}(t)} SoC_{dep}(i,t), \forall t \tag{4.22}$$

$$DSoC(t) = SoC_{dep}^{total}(t) - SoC_{arr}^{total}(t), \forall t \tag{4.23}$$

, where n_{arr} and n_{dep} are the total amount of vehicles that arrive and depart from the charging station accordingly.

After calculating the $DSoC$ and the dynamic boundries for the Aggregated Energy for every t, the Aggregated upper and lower limits of the energy and power are calculated, as follows:

$$SoC_{max}^{aggr}(t) = \sum_{i=1}^{n(t)} SoC_{max}(i,t) + \sum_{k=1}^{t} DSoC(t), \forall t \tag{4.24}$$

$$SoC_{min}^{aggr}(t) = \sum_{i=1}^{n(t)} SoC_{min}(i,t) + \sum_{k=1}^{t} DSoC(t), \forall t \tag{4.25}$$

$$P^{aggr}_{max}(t) = \sum_{i=1}^{n(t)} P_{max}(i,t), \forall t \tag{4.26}$$

$$P^{aggr}_{min}(t) = \sum_{i=1}^{n(t)} P_{min}(i,t), \forall t \tag{4.27}$$

4.7 RES Optimal Utilization

In order to utilize the V2G function in correlation with the Aggregator, a random day was chosen from which the energy produced by RES should be preffered over the traditional Energy sources. The problem deduces to a minimization of the Net Load of Crete (which is the RES production substracted from the total load). The Net load is then normalized to better resemble the electricity price, that way the Virtual Electricity Price is produced, such as:

$$VEP(t) = \frac{net\ load(t)}{max(net\ load)} \tag{4.28}$$

Moreover the Aggregator was used both as a load, as well as an energy source.

$$min(P_{EV} \times VEP) \tag{4.29}$$

All the vehicles together form a battery that charges and discharges, so it both takes and gives power to the grid. Also regarding fmincon it is:

$$SoC_f - SoC_0 = \sum_{i=1}^{t} P_{EV}, \forall t \tag{4.30}$$

The boundries regarding the EV power are:

$$P^{aggr}_{min}(t) \leq P_{EV}(t) \leq P^{aggr}_{min}(t), \forall t \tag{4.31}$$

and as for the maximum and minimum value of the battery capacity :

$$\sum_{k=1}^{t} P_{EV} \times dt \leq SoC^{aggr}_{max}(t) - SoC_0, \forall t \tag{4.32}$$

$$\sum_{k=1}^{t} P_{EV} \times dt \geq SoC^{aggr}_{min}(t) - SoC_0, \forall t \tag{4.33}$$

CHAPTER 5

Modeling Results

5.1 Modeling Results of Crete Power Grid without electric vehicles and with different penetration scenarios of electric vehicles

In this chapter various results will be shown regarding different penetration scenarios of electric vehicles in the power grid of Crete. The parameters changing in this model according to every scenario are the total load as well as the contibution of RES. Three different scenarios are studied here, based on the adoption percentage of EVs in the Helenic market. The main results regard:

- The loads of Electric Vehicles
- The total load on the Power grid
- The energy contributed by the RES
- The energy given back to the grid by Electric Vehicles

The main objective is to optimize the EV load and consequently the fuel cost. This will result in even ”greener” electric vehicles.

5.2 Modeling Results without any Electric vehicle penetration

Firstly, it is important to establish a baseline in wich we can see the load in the iland, without the use of any Electric Vehicles. This way the contribution of RES is more easily comprehended. In Figure 5.1 it is apparent that wind and solar help the total load, depending on the time of day and their energy production. Finaly the rush hours can be aproximated between 14:00 and 23:00, since both the consumer and the industrial energy demand is high.

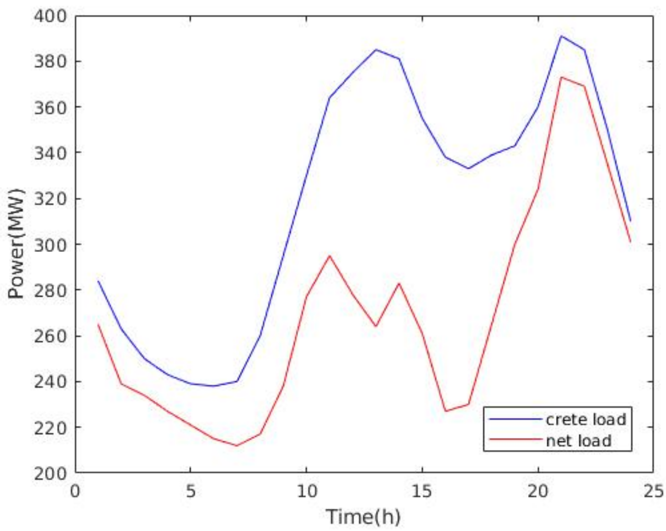

Figure 5.1. The daily load graph including net and real loads.(17/07/2018)

5.3 EV Penetration scenarios

In this thesis the modeling took place in regards to the aproximated EV penetration percentage until 2030. There are four scenarios :

- Low EV penetration: The most likely scenario, according to which the EVs will reach 10% of the total fleet until 2030.
- Medium EV penetration: A more optimistic scenario, according to which the EVs will reach 15% of the total fleet until 2030.

- High EV penetration: A more aggresive scenario, according to which the EVs will reach 30% of the total fleet until 2030.
- Ultra High EV penetration: The most aggresive scenario, according to which the EVs will reach 45% of the total fleet until 2030.

The estimated number of vehicles in Crete is 498.454 vehicles. According the each county's population, a vehicle percentage was calculated based on the total population of the island. More specific Chania has 25.17% of the total population, Heraklion 49%, Rethymno 13.73% and Lasithi has 12.1%. By multipling these percentages with the total number of vehicles in Crete, we get the number of all vehicles in each county. In the following Table 5.1 the total number of vehicles is presented, alongside the number of EVs in every scenario.

County	Vehicles	Low(10%)	Medium(15%)	High(30%)	Ultra High(45%)
Heraklion	244.242	24.424	36.636	73.273	109.909
Chania	125.461	12.546	18.819	37.638	56.457
Rethymno	68.438	6.844	10.266	20.531	30.797
Lasithi	60.313	6.031	9.047	18.094	27.141
Total	498.454	49.845	74.768	149.536	224.304

Table 5.1. Number of EVS in Crete in 2030, with multiple penetration scenarios.

Taking into consideration that more RES may be constructed and added to the grid by 2030, two more cases were studied, such as the RES production is increased by 50% and by 75%. These case were also studied with the scenarios mentioned above.

5.4 Day-Schedule Modeling Results

In Figure 5.2 the position of the vehicles during the day is presented. It is clear that during the night very few vehicles are moving, since most of them are parked home. During the day most of the vehicles are either on move ro at work or on social activities, and tend to go back home after 15:00.

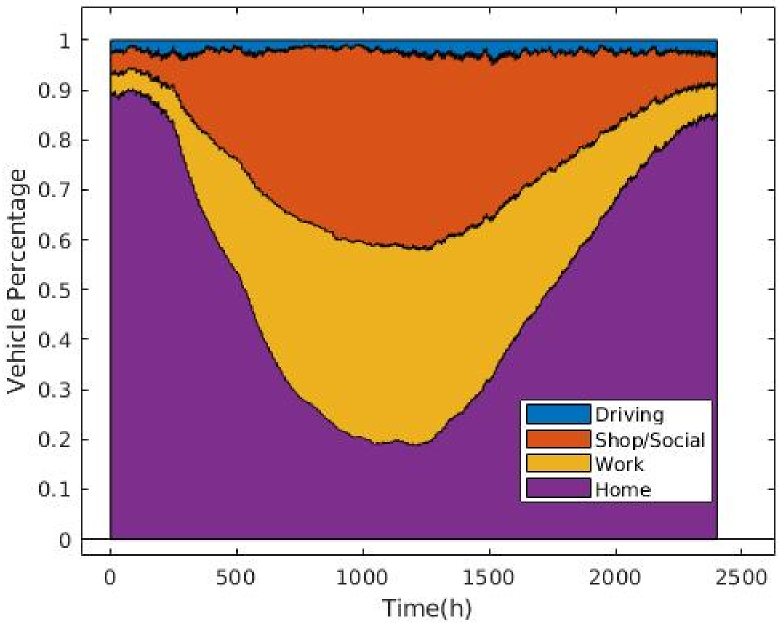

Figure 5.2. The distribution of EVs location during the day

In Figure 5.3 the percentage of EVs charging at any given moment during the day. Like we saw before, there is a dip during the middle of the day, logical, since this is when most people return from work or spend time in social activities.

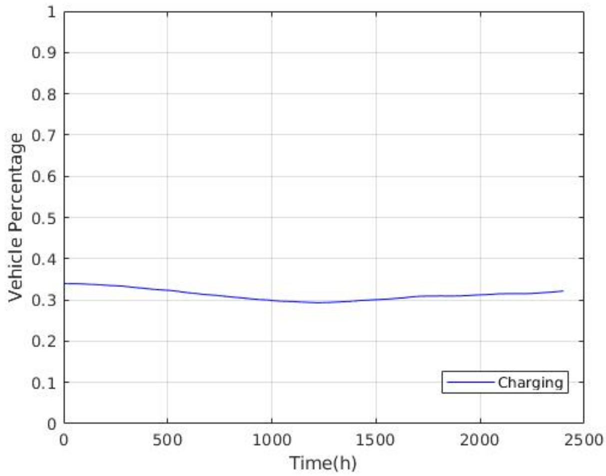

Figure 5.3. The percentage of cars changing during the day

5.5 Baseline RES Production

5.5.1 Low EV penetration scenario modeling results

5.5.1.1 Dumb Charging

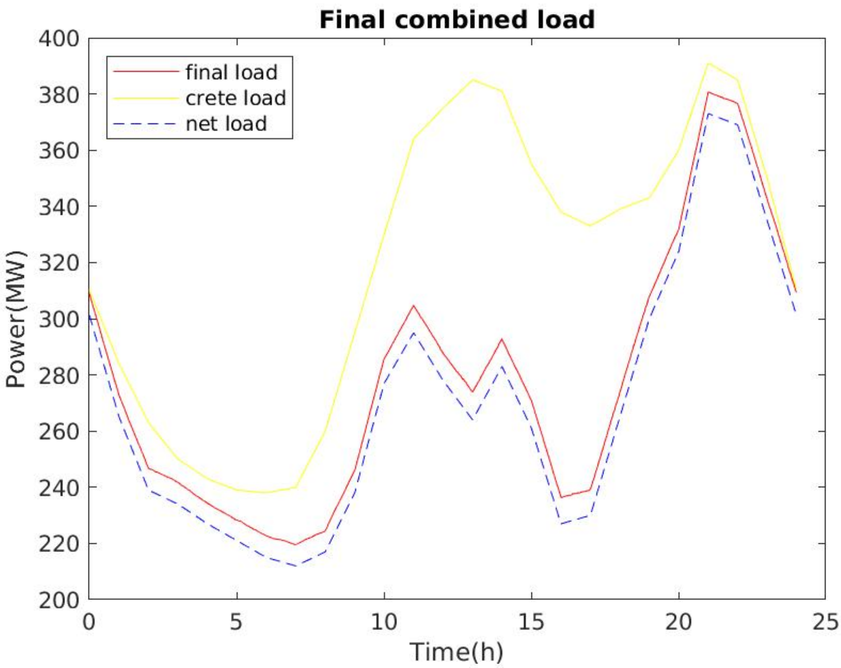

Figure 5.4. Total load with and without EVs: Low scenario (Dumb Charging)

During Dumb Charging the vehicles draw from the grid a stable amount of Power for the duration of charging. In this scenario the total amount of vehicles is 49.485 EVs and the Power drawn in peak hours (15:00) reaches 18 MW. In this scenario as can be seen by the graph in Figure 5.4 the EVs can be powered almost exclusively from RES since the final load (net load + EV load) is under the original Crete load (which has the RES included, contradictory to the net load).

5.5.1.2 Vehicle Based Smart/Optimal Charging

During Smart Charging the vehicles adjusts the power drawn from the grid, in relation to the net load the island has. That way the vehicle can give power back to the grid when it deems that the grid is pushed. In this scenario the total amount of vehicles

is 49.485 EVs and the Power drawn in peak hours (15:00) reaches 18 MW. In this scenario as can be seen by the graph in Figure 5.5 the EVs can be powered almost exclusively from RES since the final load (net load + EV load) is under the original Crete load (which has the RES included, contradictory to the net load). But this is not the main benefit of this method, since it can be seen that it tends to normalize and flatten the load of Crete.

5.5.1.3 Aggregator Controlled Charging

Using this V2G Charging method the EVs have the ability to return power back to the grid when necessary. In this method of changing the Aggregator determines when the vehicles will charge or discharge with the goal of maximizing the use of RES produced energy in the grid of Crete for 24 hours. By comparing the graphs in Figures 5.4, 5.5 it is observed that the Load graph as formed using the Aggregator method more closely resembles the net load one, with it giving power back to the grid when most necessary (e.g. around 21:30). In Figure 5.6 the power drawn by EVs follows the graph above when inverted, which shows the Virtual Electicity Price (which is the Net Load normalized). This means that when the Net Load (Load of Crete with RES substracted) is high, the power demand of the EVs is low. During unproductive hours for RES the power demand lessens comparing to the other methods. (i.e. around 02:00) In addition the EV power demand is higher during productive hours for RES (i.e around 15:00)

5.5.1.4 Comparison

In this Scenario when comparing the two methods (*Vehicle Based Smart/Optimal Charging* and *Aggregator Controlled Charging*) it is apparent that the are close to each other, while the latter more closely follows the curve of the net load. Here the *Vehicle Based Smart/Optimal Charging* method performs better, since the final load graph seems to be more straight, so it is more beneficial to the grid. From the other hand the *Aggregator Controlled Charging* method doesn't require any more calculation from the Electricity providers(regarding which Power Station should be powered on or off), because it works in relation to them.

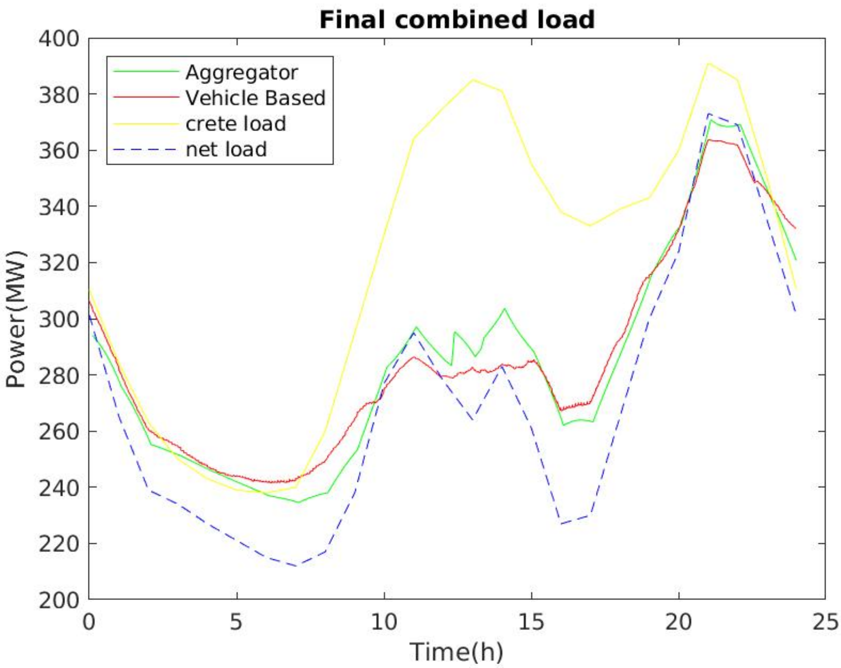

Figure 5.5. Total load with and without EVs: Low scenario (V2G Charging)

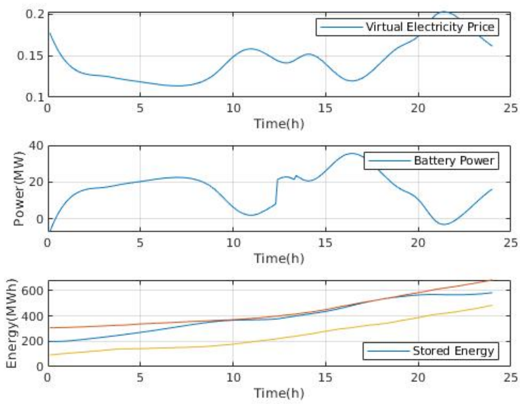

Figure 5.6. The Power generated by RES, the power of the aggregated battery and the total amount of Energy in a day: Low scenario (V2G)

5.5.2 Medium EV penetration scenario modeling results

5.5.2.1 Dumb Charging

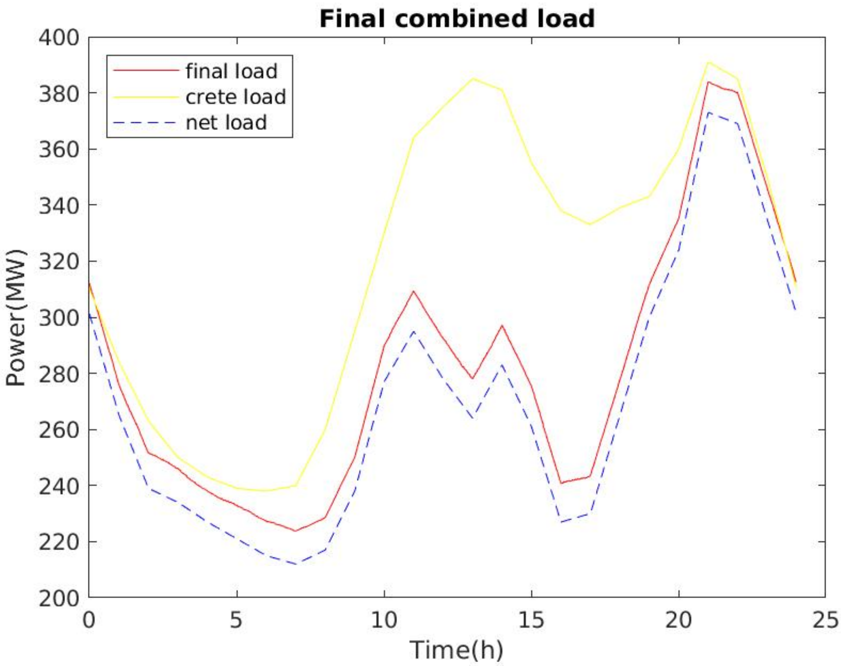

Figure 5.7. Total load with and without EVs: Medium scenario (Dumb Charging)

During Dumb Charging the vehicles draw from the grid a stable amount of Power for the duration of charging. In this scenario the total amount of vehicles is 74.768 EVs and the Power drawn in peak hours (15:00) reaches 27 MW. In this scenario as can be seen by the graph in Figure 5.7 the EVs cannot be powered exclusively from RES since the final load (net load + EV load) is over the original Crete load (which has the RES included, contradictory to the net load). This can be seen mostly when the RES production is at its lowest.

5.5.2.2 Vehicle Based Smart/Optimal Charging

During Smart Charging the vehicles adjusts the power drawn from the grid, in relation to the net load the island has. That way the vehicle can give power back to the grid when it deems that the grid is pushed. In this scenario the total amount of vehicles is 74.768 EVs and the Power drawn in peak hours (15:00) reaches 27 MW. In this scenario as can be seen by the graph in Figure 5.8 the EVs cannot be powered exclusively from RES since the final load (net load + EV load) is over the original Crete load (which has the RES included, contradictory to the net load) in some cases. But this is not the main benefit of this method, since it can be seen that it tends to normalize and flatten the load of Crete.

5.5.2.3 Aggregator Controlled Charging

Using the V2G Charging method the EVs have the ability to return power back to the grid when necessary. In this method of changing the Aggregator determines when the vehicles will charge or discharge with the goal of maximizing the use of RES produced energy in the grid of Crete for 24 hours. By comparing the graphs in Figures 5.7, 5.8 it is observed that the Load graph as formed using the Aggregator method more closely resembles the net load one, with it giving power back to the grid when most necessary (e.g. around 21:30). In Figure 5.9 the power drawn by EVs follows the graph above when inverted, which shows the Virtual Electicity Price (which is the Net Load normalized). This means that when the Net Load (Load of Crete with RES substracted) is high, the power demand of the EVs is low. During unproductive hours for RES the power demand lessens comparing to the other methods. (i.e. around 02:00) In addition the EV power demand is higher during productive hours for RES (i.e around 15:00)

5.5.2.4 Comparison

In this Scenario when comparing the two methods (*Vehicle Based Smart/Optimal Charging* and *Aggregator Controlled Charging*) it is apparent that the are no longer that close to each other. Here with the *Vehicle Based Smart/Optimal Charging* method, the final load graph seems to have more small peaks and valleys, but still manages to be quite straight, so it is beneficial to the grid.The peaks and valleys are generated, because each vehicle calculates on its own when it should draw or give power from and to the grid. From the other hand the *Aggregator Controlled Charging* load continues to follow the curvature of the net load, in the most part (while being smoother when compared to lower penetration scenarios), while mostly emphasizing drawing power when the net load is at its lowest, and it gives back to the grid, while the net load is at its highest.

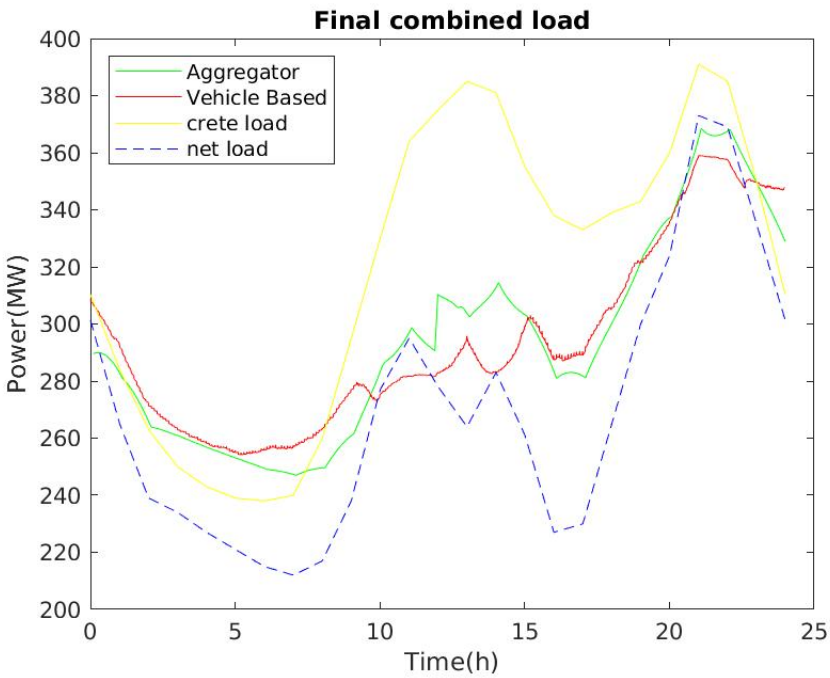

Figure 5.8. Total load with and without EVs: Medium scenario (V2G Charging)

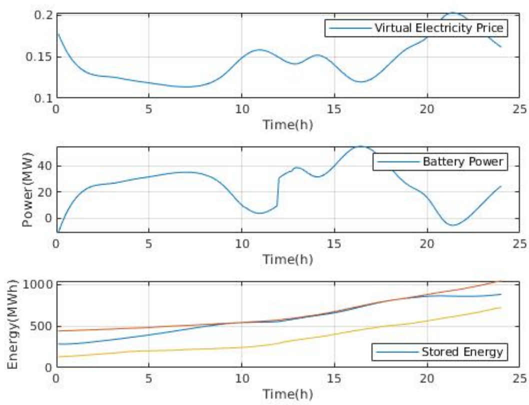

Figure 5.9. The Power generated by RES, the power of the aggregated battery and the total amount of Energy in a day: Medium scenario (V2G)

5.5.3 High EV penetration scenario modeling results

5.5.3.1 Dumb Charging

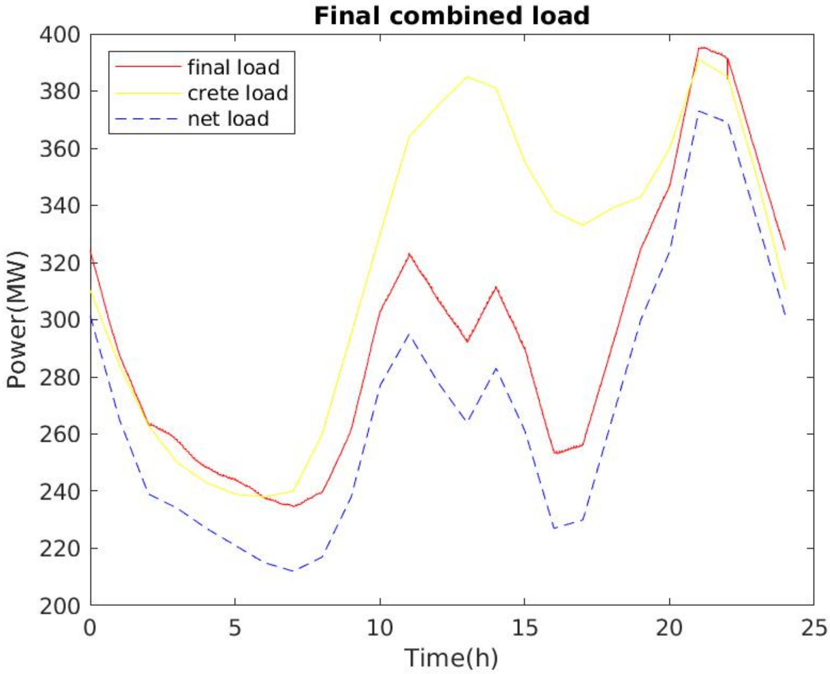

Figure 5.10. Total load with and without EVs: High scenario (Dumb Charging)

During Dumb Charging the vehicles draw from the grid a stable amount of Power for the duration of charging. In this scenario the total amount of vehicles is 149.536 EVs and the Power drawn in peak hours (15:00) reaches 54 MW. In this scenario as can be seen by the graph in Figure 5.10 the EVs cannot be powered from RES since the final load (net load + EV load) is over the original Crete load (which has the RES included, contradictory to the net load). This can be seen mostly when the RES production is at its lowest.

5.5.3.2 Vehicle Based Smart/Optimal Charging

During Smart Charging the vehicles adjusts the power drawn from the grid, in relation to the net load the island has. That way the vehicle can give power back to the grid when it deems that the grid is pushed. In this scenario the total amount of vehicles is 149.536 EVs and the Power drawn in peak hours (15:00) reaches 54 MW. In this scenario as can be seen by the graph in Figure 5.11 the EVs cannot be powered from

RES since the final load (net load + EV load) is over the original Crete load (which has the RES included, contradictory to the net load). Here with a higher volume of vehicles, the benefits of this method tend to lessen, since the load is not flat or even close to it. This is happening because each EV acts independenty and all the vehicles give power back to the grid or even preffer to lessen the power drawn at the same periods of the day.

5.5.3.3 Aggregator Controlled Charging

Using the V2G Charging method the EVs have the ability to return power back to the grid when necessary. In this method of changing the Aggregator determines when the vehicles will charge or discharge with the goal of maximizing the use of RES produced energy in the grid of Crete for 24 hours. By comparing the graphs in Figures 5.10, 5.11 it is observed that the Load graph as formed using the Aggregator method resembles the net load one, while being smoother overall.

In Figure 5.12 the power drawn by EVs follows the graph above when inverted, which shows the Virtual Electicity Price (which is the Net Load normalized). This means that when the Net Load (Load of Crete with RES substracted) is high, the power demand of the EVs is low. During unproductive hours for RES the power demand lessens comparing to the other methods. (i.e. around 02:00) In addition the EV power demand is higher during productive hours for RES (i.e around 15:00)

5.5.3.4 Comparison

In this Scenario when comparing the two methods (*Vehicle Based Smart/Optimal Charging* and *Aggregator Controlled Charging*) it is apparent that the are now completely different from each other, since the first now resembles and inverted netload. Here with the *Vehicle Based Smart/Optimal Charging* method, the final load graph seems to have high peaks and valleys, deeming it no longer beneficial to the grid. The peaks and valleys are generated, because each vehicle calculates on its own when it should draw or give power from and to the grid. On the other hand the *Aggregator Controlled Charging* load no longer continues to follow the curvature of the net load, but manages to become a lot smoother when compared to lower penetration scenarios. In this scenario we are beginig to see the benefits of the Aggregator model, since it starts to be a lot smoother, which is very beneficial to the grid.

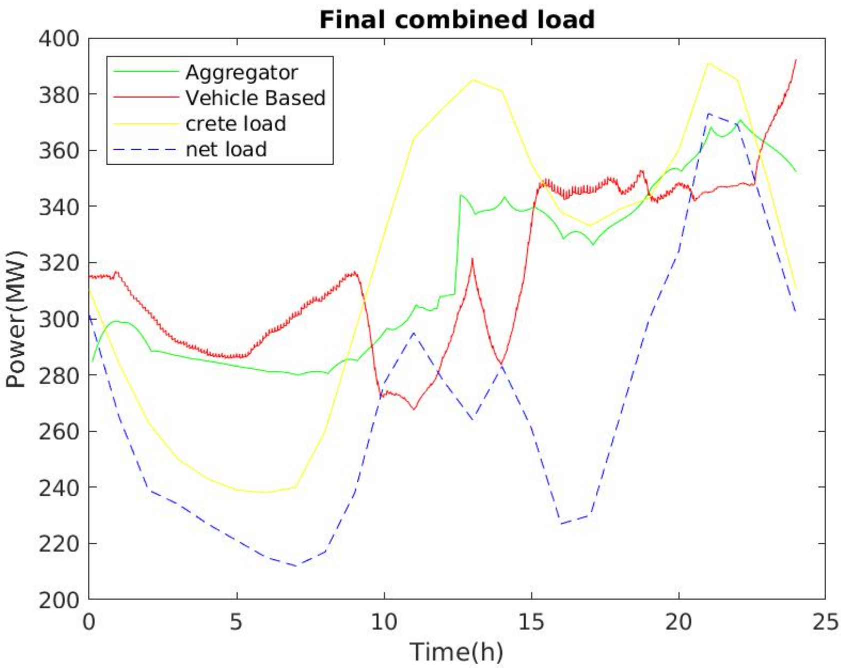

Figure 5.11. Total load with and without EVs: High scenario (V2G Charging)

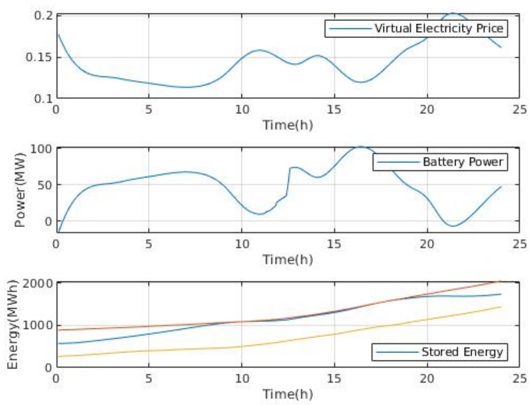

Figure 5.12. The Power generated by RES, the power of the aggregated battery and the total amount of Energy in a day: High scenario (V2G)

5.5.4 Ultra High EV penetration scenario modeling results

5.5.4.1 Dumb Charging

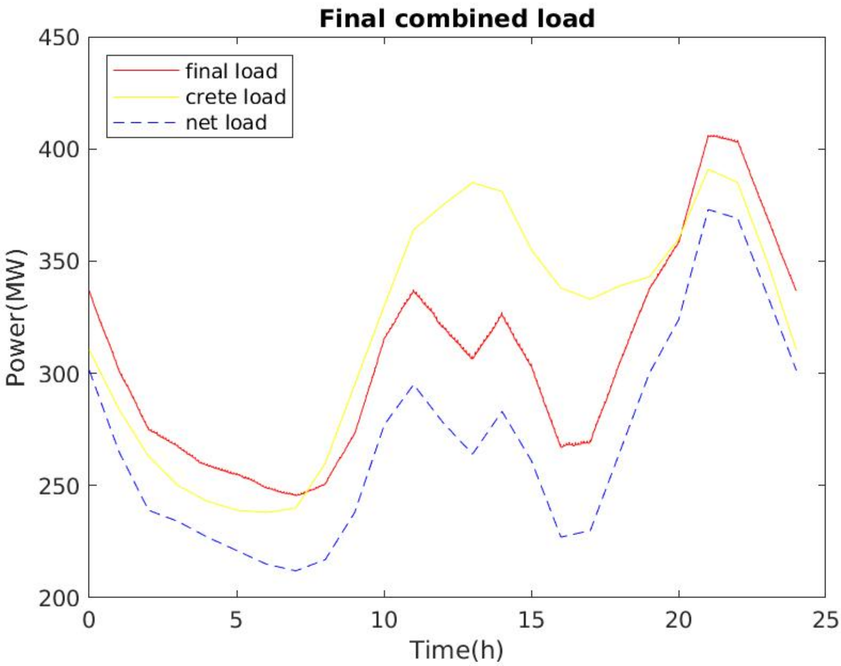

Figure 5.13. Total load with and without EVs: Ultra High scenario (Dumb Charging)

During Dumb Charging the vehicles draw from the grid a stable amount of Power for the duration of charging. In this scenario the total amount of vehicles is 224.304 EVs and the Power drawn in peak hours (15:00) reaches 81 MW. In this scenario as can be seen by the graph in Figure 5.13 the EVs cannot be powered from RES since the final load (net load + EV load) is over the original Crete load (which has the RES included, contradictory to the net load). This can be seen mostly in the majority of the graph, but is examplified during low RES production.

5.5.4.2 Vehicle Based Smart/Optimal Charging

During Smart Charging the vehicles adjusts the power drawn from the grid, in relation to the net load the island has. That way the vehicle can give power back to the grid when it deems that the grid is pushed. In this scenario the total amount of vehicles is 224.304 EVs and the Power drawn in peak hours (15:00) reaches 81 MW. In this scenario as can be seen by the graph in Figure **??** the EVs cannot be powered from

RES since the final load (net load + EV load) is over the original Crete load (which has the RES included, contradictory to the net load). Here with a higher volume of vehicles, the benefits of this method tend to lessen, since the load is not flat or even close to it. This is happening because each EV acts independenty and all the vehicles give power back to the grid or even preffer to lessen the power drawn at the same periods of the day. In this scenario the sideffects of the Smart Charging method are examplified.

5.5.4.3 Aggregator Controlled Charging

Using the V2G Charging method the EVs have the ability to return power back to the grid when necessary. In this method of changing the Aggregator determines when the vehicles will charge or discharge with the goal of maximizing the use of RES produced energy in the grid of Crete for 24 hours. By comparing the graphs in Figures 5.13, 5.14 it is observed that the Load graph as formed using the Aggregator method is now almost smooth and straight.

In Figure 5.15 the power drawn by EVs follows the graph above when inverted, which shows the Virtual Electicity Price (which is the Net Load normalized). This means that when the Net Load (Load of Crete with RES substracted) is high, the power demand of the EVs is low. During unproductive hours for RES the power demand lessens comparing to the other methods. (i.e. around 02:00) In addition the EV power demand is higher during productive hours for RES (i.e around 15:00)

5.5.4.4 Comparison

In this Scenario when comparing the two methods (*Vehicle Based Smart/Optimal Charging* and *Aggregator Controlled Charging*) it is apparent that the are now completely different from each other, since the first now resembles and inverted and examplified netload. Here with the *Vehicle Based Smart/Optimal Charging* method, the final load graph seems to have very high peaks and valleys, deeming it no longer beneficial to the grid. The peaks and valleys are generated, because each vehicle calculates on its own when it should draw or give power from and to the grid. On the other hand the *Aggregator Controlled Charging* load is a lot smoother when compared to lower penetration scenarios. In this scenario we see the benefits of the Aggregator model, since it starts to be a lot smoother, which is very beneficial to the grid. So it can be concluded that the Aggregator Controlled Charging performs better on higher EV penetration scenarios, while the Vehicle Based Smart/Optimal Charging is better when the EV penetration is lower.

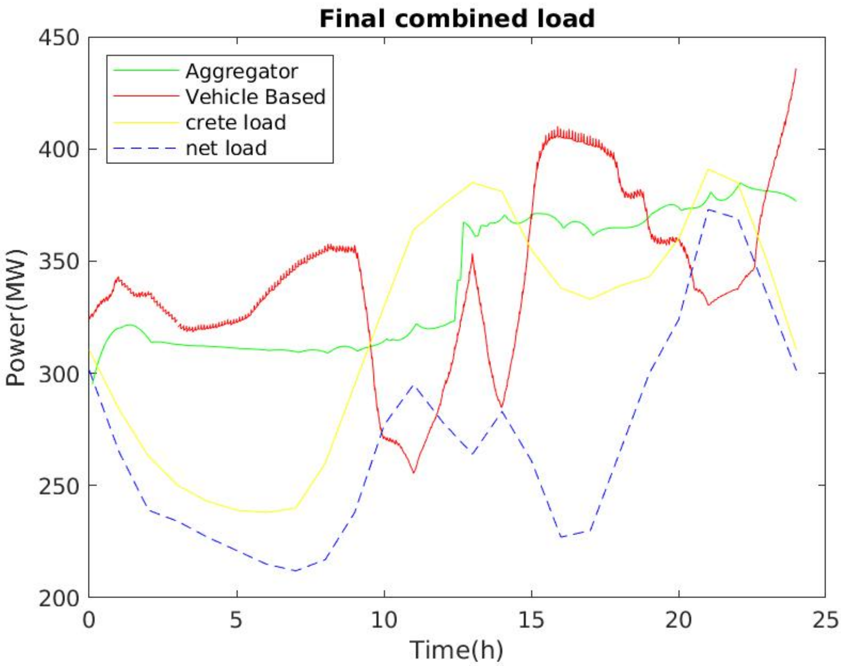

Figure 5.14. Total load with and without EVs: Ultra High scenario (V2G Charging)

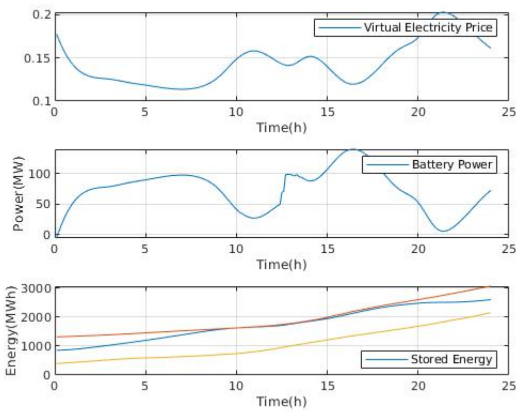

Figure 5.15. The Power generated by RES, the power of the aggregated battery and the total amount of Energy in a day: Ultra High scenario (V2G)

5.6 RES Production Increased by 50%

5.6.1 Low EV penetration scenario modeling results

5.6.1.1 Dumb Charging

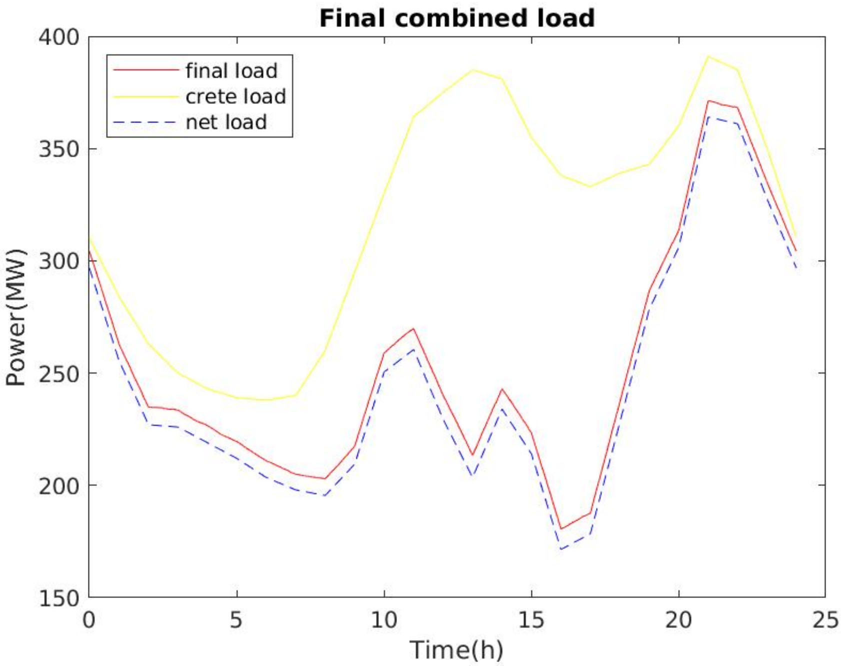

Figure 5.16. Total load with and without EVs: Low scenario (Dumb Charging)

During Dumb Charging the vehicles draw from the grid a stable amount of Power for the duration of charging. In this scenario the total amount of vehicles is 49.485 EVs and the Power drawn in peak hours (15:00) reaches 18 MW. In this scenario as can be seen by the graph in Figure 5.28 the EVs can be powered exclusively from RES since the final load (net load + EV load) is under the original Crete load (which has the RES included, contradictory to the net load).

5.6.1.2 Vehicle Based Smart/Optimal Charging

During Smart Charging the vehicles adjusts the power drawn from the grid, in relation to the net load the island has. That way the vehicle can give power back to the grid when it deems that the grid is pushed. In this scenario the total amount of vehicles

is 49.485 EVs and the Power drawn in peak hours (15:00) reaches 18 MW. In this scenario as can be seen by the graph in Figure 5.29 the EVs can be powered almost exclusively from RES since the final load (net load + EV load) is under the original Crete load (which has the RES included, contradictory to the net load). But this is not the main benefit of this method, since it can be seen that it tends to normalize and flatten the load of Crete.

5.6.1.3 Aggregator Controlled Charging

Using the V2G Charging method the EVs have the ability to return power back to the grid when necessary. In this method of changing the Aggregator determines when the vehicles will charge or discharge with the goal of maximizing the use of RES produced energy in the grid of Crete for 24 hours. By comparing the graphs in Figures 5.28, 5.29 it is observed that the Load graph as formed using the Aggregator method more closely resembles the net load one, with it giving power back to the grid when most necessary (e.g. around 21:30). In Figure 5.30 the power drawn by EVs follows the graph above when inverted, which shows the Virtual Electicity Price (which is the Net Load normalized). This means that when the Net Load (Load of Crete with RES substracted) is high, the power demand of the EVs is low. During unproductive hours for RES the power demand lessens comparing to the other methods. (i.e. around 02:00) In addition the EV power demand is higher during productive hours for RES (i.e around 15:00)

5.6.1.4 Comparison

In this Scenario when comparing the two methods (*Vehicle Based Smart/Optimal Charging* and *Aggregator Controlled Charging*) it is apparent that the are close to each other, while the latter more closely follows the curve of the net load. Here the *Vehicle Based Smart/Optimal Charging* method performs better, since the final load graph seems to be more straight, so it is more beneficial to the grid. From the other hand the *Aggregator Controlled Charging* method doesn't require any more calculation from the Electricity providers(regarding which Power Station should be powered on or off), because it works in relation to them. In this RES production case, it seems that the EVs in this low scenario can be charged exclusively by using RES. This was expected, since the RES production increaced and was able to satisfy a larger load.

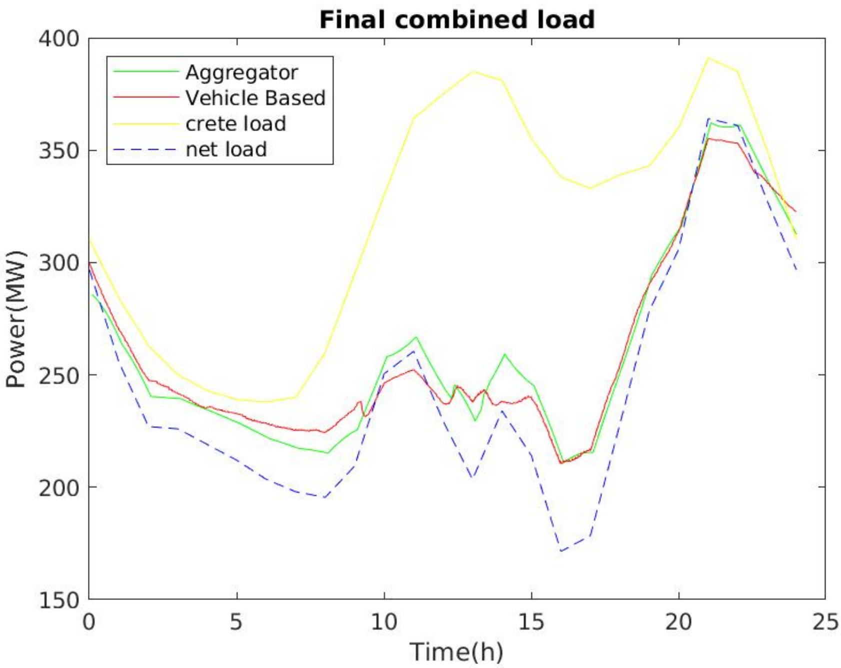

Figure 5.17. Total load with and without EVs: Low scenario (V2G Charging)

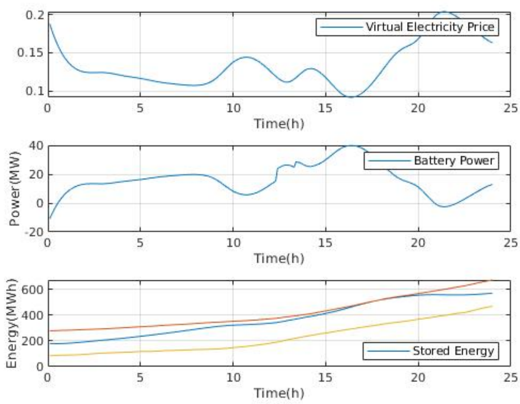

Figure 5.18. The Power generated by RES, the power of the aggregated battery and the total amount of Energy in a day: Low scenario (V2G)

5.6.2 Medium EV penetration scenario modeling results

5.6.2.1 Dumb Charging

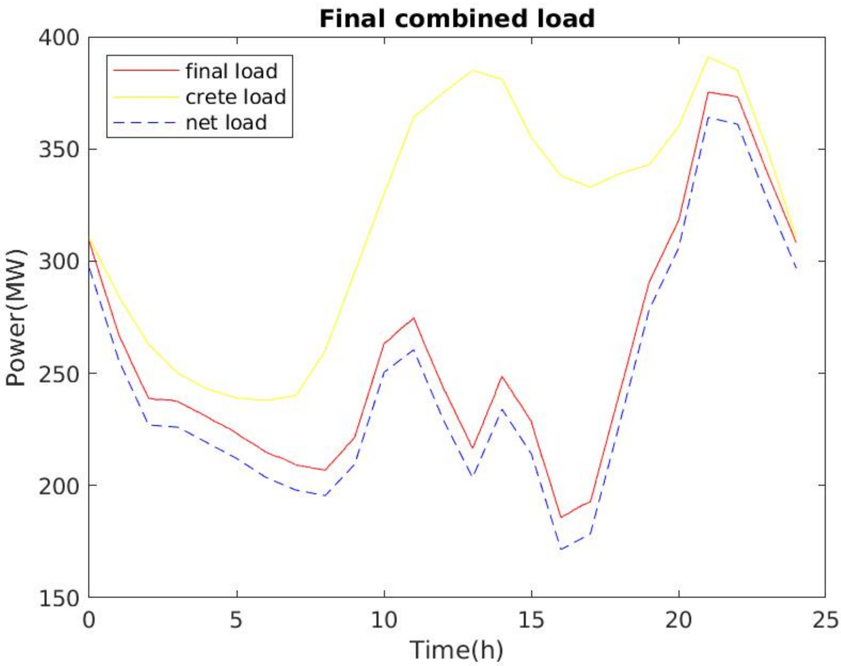

Figure 5.19. Total load with and without EVs: Medium scenario (Dumb Charging)

During Dumb Charging the vehicles draw from the grid a stable amount of Power for the duration of charging. In this scenario the total amount of vehicles is 74.768 EVs and the Power drawn in peak hours (15:00) reaches 27 MW. In this scenario as can be seen by the graph in Figure 5.31 the EVs can be powered almost exclusively from RES since the final load (net load + EV load) is under the original Crete load (which has the RES included, contradictory to the net load).

5.6.2.2 Vehicle Based Smart/Optimal Charging

During Smart Charging the vehicles adjusts the power drawn from the grid, in relation to the net load the island has. That way the vehicle can give power back to the grid when it deems that the grid is pushed. In this scenario the total amount of vehicles is 74.768 EVs and the Power drawn in peak hours (15:00) reaches 27 MW. In this scenario as can be seen by the graph in Figure 5.32 the EVs cannot be powered exclusively from RES since the final load (net load + EV load) is over the original

Crete load (which has the RES included, contradictory to the net load) in some cases. But this is not the main benefit of this method, since it can be seen that it tends to normalize and flatten the load of Crete.

5.6.2.3 Aggregator Controlled Charging

Using the V2G Charging method the EVs have the ability to return power back to the grid when necessary. In this method of changing the Aggregator determines when the vehicles will charge or discharge with the goal of maximizing the use of RES produced energy in the grid of Crete for 24 hours. By comparing the graphs in Figures 5.31, 5.32 it is observed that the Load graph as formed using the Aggregator method more closely resembles the net load one, with it giving power back to the grid when most necessary (e.g. around 21:30). In Figure 5.33 the power drawn by EVs follows the graph above when inverted, which shows the Virtual Electicity Price (which is the Net Load normalized). This means that when the Net Load (Load of Crete with RES substracted) is high, the power demand of the EVs is low. During unproductive hours for RES the power demand lessens comparing to the other methods. (i.e. around 02:00) In addition the EV power demand is higher during productive hours for RES (i.e around 15:00)

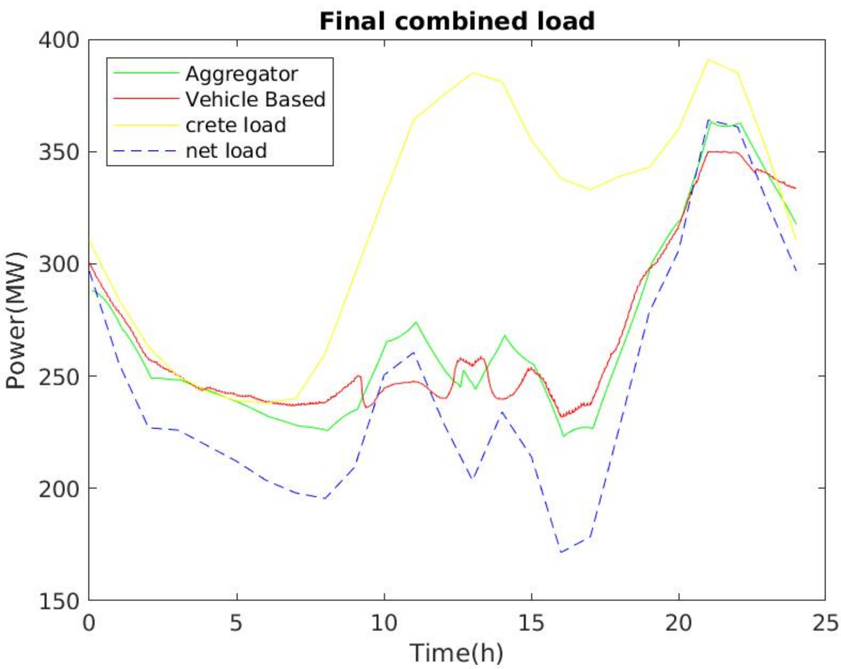

Figure 5.20. Total load with and without EVs: Medium scenario (V2G Charging)

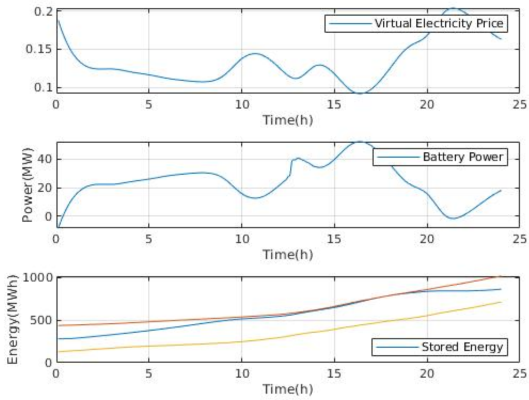

Figure 5.21. The Power generated by RES, the power of the aggregated battery and the total amount of Energy in a day: Medium scenario (V2G)

5.6.2.4 Comparison

In this Scenario when comparing the two methods (*Vehicle Based Smart/Optimal Charging* and *Aggregator Controlled Charging*) it is apparent that the are no longer that close to each other. Here with the *Vehicle Based Smart/Optimal Charging* method, the final load graph seems to have more small peaks and valleys, but still manages to be quite straight, so it is beneficial to the grid.The peaks and valleys are generated, because each vehicle calculates on its own when it should draw or give power from and to the grid. From the other hand the *Aggregator Controlled Charging* load continues to follow the curvature of the net load, in the most part (while being smoother when compared to lower penetration scenarios), while mostly emphasizing drawing power when the net load is at its lowest, and it gives back to the grid, while the net load is at its highest.

Here it is apparent that while the *Aggregator Controlled Charging* method is not that smooth, the EVs can be powered exclusively by using RES. Moreover, the load generated by using the *Vehicle Based Smart/Optimal Charging* method is smoother, when comparing it to the same penetration scenario, but with fewer RES.

5.6.3 High EV penetration scenario modeling results

5.6.3.1 Dumb Charging

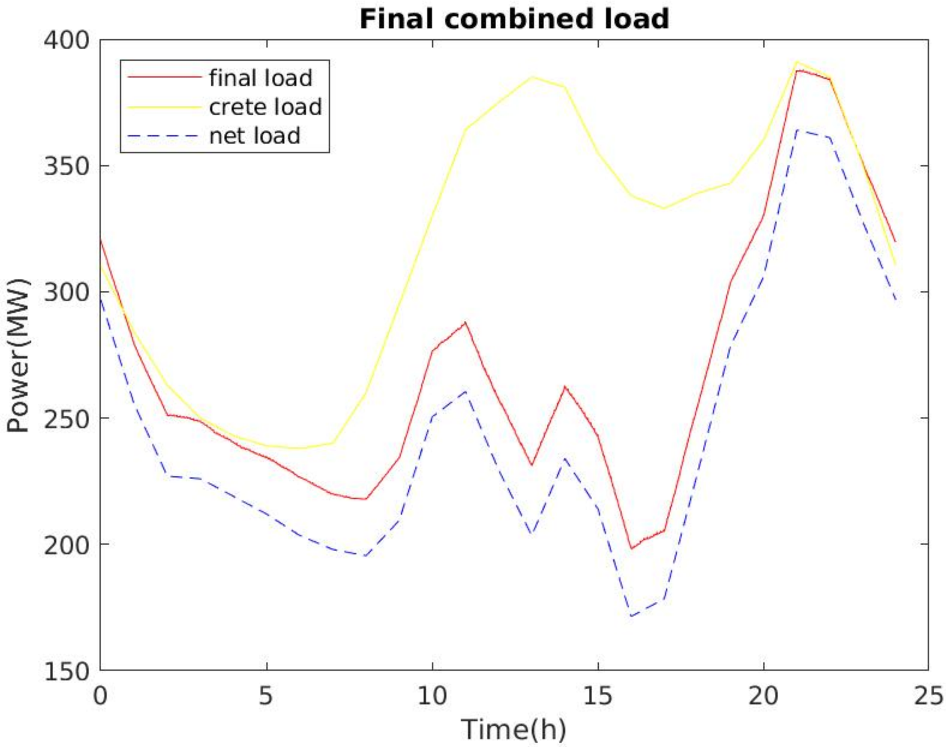

Figure 5.22. Total load with and without EVs: High scenario (Dumb Charging)

During Dumb Charging the vehicles draw from the grid a stable amount of Power for the duration of charging. In this scenario the total amount of vehicles is 149.536 EVs and the Power drawn in peak hours (15:00) reaches 54 MW. In this scenario as can be seen by the graph in Figure 5.34 the EVs cannot be powered from RES since the final load (net load + EV load) is over the original Crete load (which has the RES included, contradictory to the net load). This can be seen mostly when the RES production is at its lowest.

5.6.3.2 Vehicle Based Smart/Optimal Charging

During Smart Charging the vehicles adjusts the power drawn from the grid, in relation to the net load the island has. That way the vehicle can give power back to the grid

when it deems that the grid is pushed. In this scenario the total amount of vehicles is 149.536 EVs and the Power drawn in peak hours (15:00) reaches 54 MW. In this scenario as can be seen by the graph in Figure 5.35 the EVs cannot be powered from RES since the final load (net load + EV load) is over the original Crete load (which has the RES included, contradictory to the net load). Here with a higher volume of vehicles, the benefits of this method tend to lessen, since the load is not flat or even close to it. This is happening because each EV acts independenty and all the vehicles give power back to the grid or even preffer to lessen the power drawn at the same periods of the day.

5.6.3.3 Aggregator Controlled Charging

Using the V2G Charging method the EVs have the ability to return power back to the grid when necessary. In this method of changing the Aggregator determines when the vehicles will charge or discharge with the goal of maximizing the use of RES produced energy in the grid of Crete for 24 hours. By comparing the graphs in Figures 5.34, 5.35 it is observed that the Load graph as formed using the Aggregator method resembles the net load one, while being smoother overall.

In Figure 5.36 the power drawn by EVs follows the graph above when inverted, which shows the Virtual Electicity Price (which is the Net Load normalized). This means that when the Net Load (Load of Crete with RES substracted) is high, the power demand of the EVs is low. During unproductive hours for RES the power demand lessens comparing to the other methods. (i.e. around 02:00) In addition the EV power demand is higher during productive hours for RES (i.e around 15:00)

5.6.3.4 Comparison

In this Scenario when comparing the two methods (*Vehicle Based Smart/Optimal Charging* and *Aggregator Controlled Charging*) it is apparent that the are now completely different from each other, since the first now resembles and inverted netload. Here with the *Vehicle Based Smart/Optimal Charging* method, the final load graph seems to have high peaks and valleys, deeming it no longer beneficial to the grid. The peaks and valleys are generated, because each vehicle calculates on its own when it should draw or give power from and to the grid. On the other hand the *Aggregator Controlled Charging* load no longer continues to follow the curvature of the net load, but manages to become a lot smoother when compared to lower penetration scenarios. In this scenario we are beginig to see the benefits of the Aggregator model, since it starts to be a lot smoother, which is very beneficial to the grid. In higher EV penetration scenarios, even the greater production of RES Energy is sufficient to make the *Vehicle Based Smart/Optimal Charging* method viable, since it has high peaks and deep valleys in the final load.

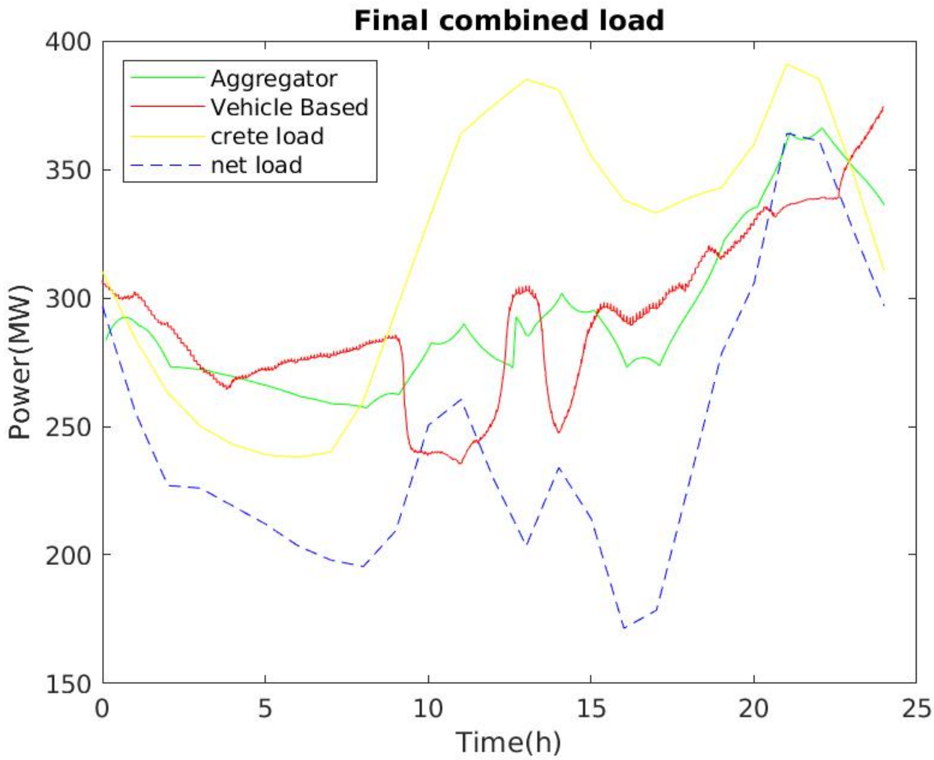

Figure 5.23. Total load with and without EVs: High scenario (V2G Charging)

5.6.4 Ultra High EV penetration scenario modeling results

5.6.4.1 Dumb Charging

During Dumb Charging the vehicles draw from the grid a stable amount of Power for the duration of charging. In this scenario the total amount of vehicles is 224.304 EVs and the Power drawn in peak hours (15:00) reaches 81 MW. In this scenario as can be seen by the graph in Figure 5.37 the EVs cannot be powered from RES since the final load (net load + EV load) is over the original Crete load (which has the RES included, contradictory to the net load). This can be seen mostly in the majority of the graph, but is examplified during low RES production.

5.6.4.2 Vehicle Based Smart/Optimal Charging

During Smart Charging the vehicles adjusts the power drawn from the grid, in relation to the net load the island has. That way the vehicle can give power back to the grid

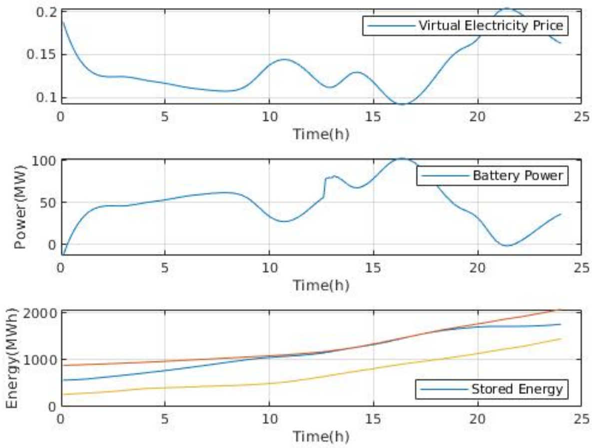

Figure 5.24. The Power generated by RES, the power of the aggregated battery and the total amount of Energy in a day: High scenario (V2G)

when it deems that the grid is pushed. In this scenario the total amount of vehicles is 224.304 EVs and the Power drawn in peak hours (15:00) reaches 81 MW. In this scenario as can be seen by the graph in Figure **??** the EVs cannot be powered from RES since the final load (net load + EV load) is over the original Crete load (which has the RES included, contradictory to the net load). Here with a higher volume of vehicles, the benefits of this method tend to lessen, since the load is not flat or even close to it. This is happening because each EV acts independenty and all the vehicles give power back to the grid or even preffer to lessen the power drawn at the same periods of the day. In this scenario the sideffects of the Smart Charging method are examplified.

5.6.4.3 Aggregator Controlled Charging

Using the V2G Charging method the EVs have the ability to return power back to the grid when necessary. In this method of changing the Aggregator determines when the vehicles will charge or discharge with the goal of maximizing the use of RES produced energy in the grid of Crete for 24 hours. By comparing the graphs in Figures 5.37, 5.38 it is observed that the Load graph as formed using the Aggregator method is now almost smooth and straight.

In Figure 5.39 the power drawn by EVs follows the graph above when inverted, which shows the Virtual Electicity Price (which is the Net Load normalized). This means that when the Net Load (Load of Crete with RES substracted) is high, the power demand of the EVs is low. During unproductive hours for RES the power

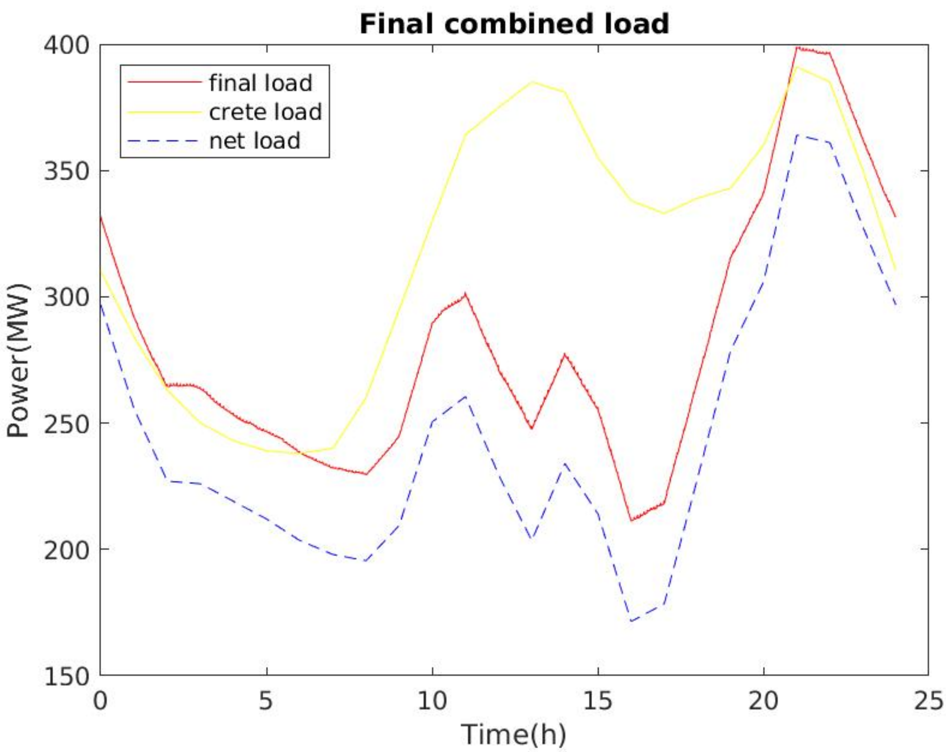

Figure 5.25. Total load with and without EVs: Ultra High scenario (Dumb Charging)

demand lessens comparing to the other methods. (i.e. around 02:00) In addition the EV power demand is higher during productive hours for RES (i.e around 15:00)

5.6.4.4 Comparison

In this Scenario when comparing the two methods (*Vehicle Based Smart/Optimal Charging* and *Aggregator Controlled Charging*) it is apparent that the are now completely different from each other, since the first now resembles and inverted and examplified netload. Here with the *Vehicle Based Smart/Optimal Charging* method, the final load graph seems to have very high peaks and valleys, deeming it no longer beneficial to the grid. The peaks and valleys are generated, because each vehicle calculates on its own when it should draw or give power from and to the grid. On the other hand the *Aggregator Controlled Charging* load is a lot smoother when compared to lower penetration scenarios. In very high EV penetration scenarios, even the greater production of RES Energy is not sufficient to make the *Vehicle Based Smart/Optimal Charging* method viable, since it has very high peaks and deep valleys in the final

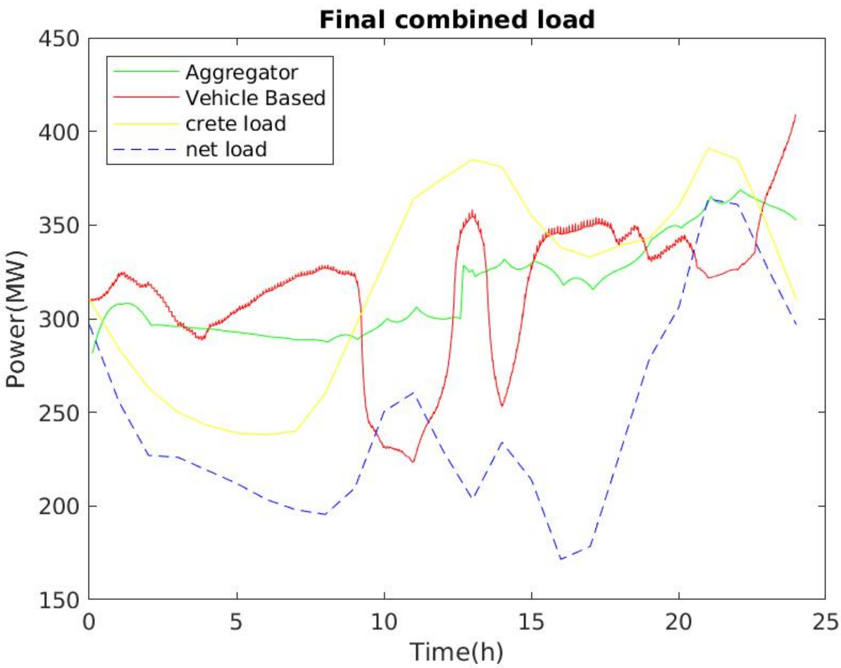

Figure 5.26. Total load with and without EVs: Ultra High scenario (V2G Charging)

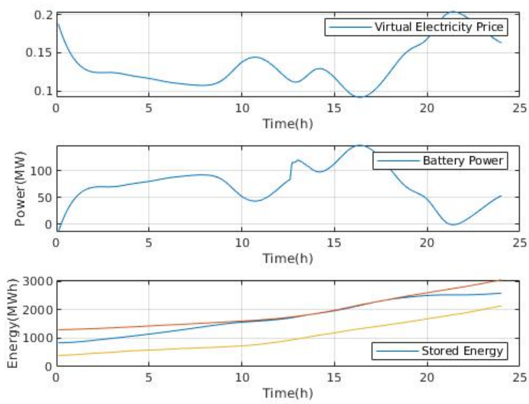

Figure 5.27. The Power generated by RES, the power of the aggregated battery and the total amount of Energy in a day: Ultra High scenario (V2G)

load.

In this scenario we see the benefits of the Aggregator model, since it starts to be a lot smoother, which is very beneficial to the grid. So it can be concluded that the Aggregator Controlled Charging performs better on higher EV penetration scenarios, while the Vehicle Based Smart/Optimal Charging is better when the EV penetration is lower, but in this case with a higher RES Production, the initial drawbacks of *Aggregator Controlled Charging* seem to lessen, making it a safer and more future proof option.

5.7 RES Production Increased by 75%

5.7.1 Low EV penetration scenario modeling results

5.7.1.1 Dumb Charging

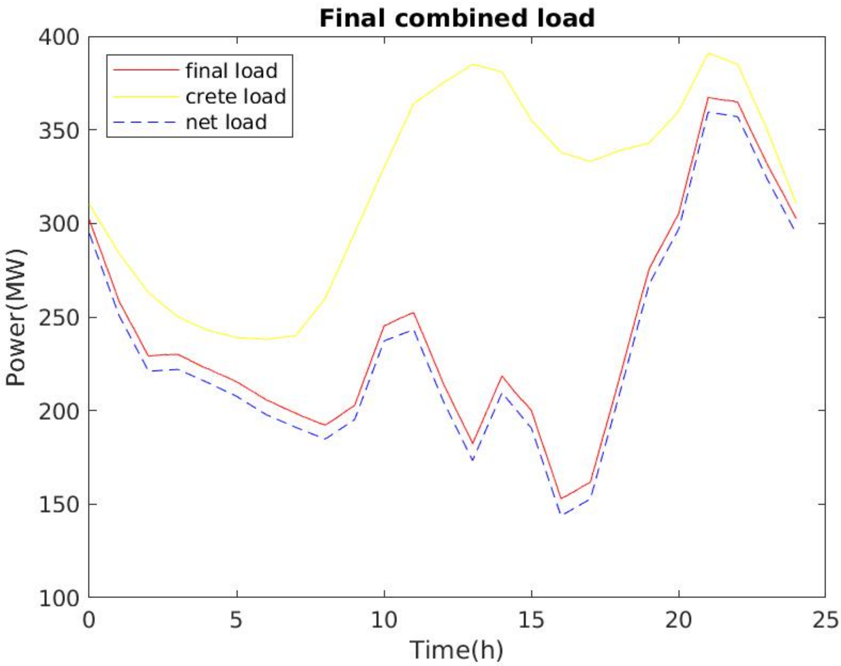

Figure 5.28. Total load with and without EVs: Low scenario (Dumb Charging)

During Dumb Charging the vehicles draw from the grid a stable amount of Power for the duration of charging. In this scenario the total amount of vehicles is 49.485 EVs and the Power drawn in peak hours (15:00) reaches 18 MW. In this scenario as can be seen by the graph in Figure 5.28 the EVs can be powered exclusively from RES since the final load (net load + EV load) is under the original Crete load (which has the RES included, contradictory to the net load).

5.7.1.2 Vehicle Based Smart/Optimal Charging

During Smart Charging the vehicles adjusts the power drawn from the grid, in relation to the net load the island has. That way the vehicle can give power back to the grid when it deems that the grid is pushed. In this scenario the total amount of vehicles

is 49.485 EVs and the Power drawn in peak hours (15:00) reaches 18 MW. In this scenario as can be seen by the graph in Figure 5.29 the EVs can be powered almost exclusively from RES since the final load (net load + EV load) is under the original Crete load (which has the RES included, contradictory to the net load). But this is not the main benefit of this method, since it can be seen that it tends to normalize and flatten the load of Crete.

5.7.1.3 Aggregator Controlled Charging

Using the V2G Charging method the EVs have the ability to return power back to the grid when necessary. In this method of changing the Aggregator determines when the vehicles will charge or discharge with the goal of maximizing the use of RES produced energy in the grid of Crete for 24 hours. By comparing the graphs in Figures 5.28, 5.29 it is observed that the Load graph as formed using the Aggregator method more closely resembles the net load one, with it giving power back to the grid when most necessary (e.g. around 21:30). In Figure 5.30 the power drawn by EVs follows the graph above when inverted, which shows the Virtual Electicity Price (which is the Net Load normalized). This means that when the Net Load (Load of Crete with RES substracted) is high, the power demand of the EVs is low. During unproductive hours for RES the power demand lessens comparing to the other methods. (i.e. around 02:00) In addition the EV power demand is higher during productive hours for RES (i.e around 15:00)

5.7.1.4 Comparison

In this Scenario when comparing the two methods (*Vehicle Based Smart/Optimal Charging* and *Aggregator Controlled Charging*) it is apparent that the are close to each other, while the latter more closely follows the curve of the net load. Here the *Vehicle Based Smart/Optimal Charging* method performs better, since the final load graph seems to be more straight, so it is more beneficial to the grid. From the other hand the *Aggregator Controlled Charging* method doesn't require any more calculation from the Electricity providers(regarding which Power Station should be powered on or off), because it works in relation to them. In this RES production case, it seems that the EVs in this low scenario can be charged exclusively by using RES. This was expected, since the RES production increaced and was able to satisfy a larger load.

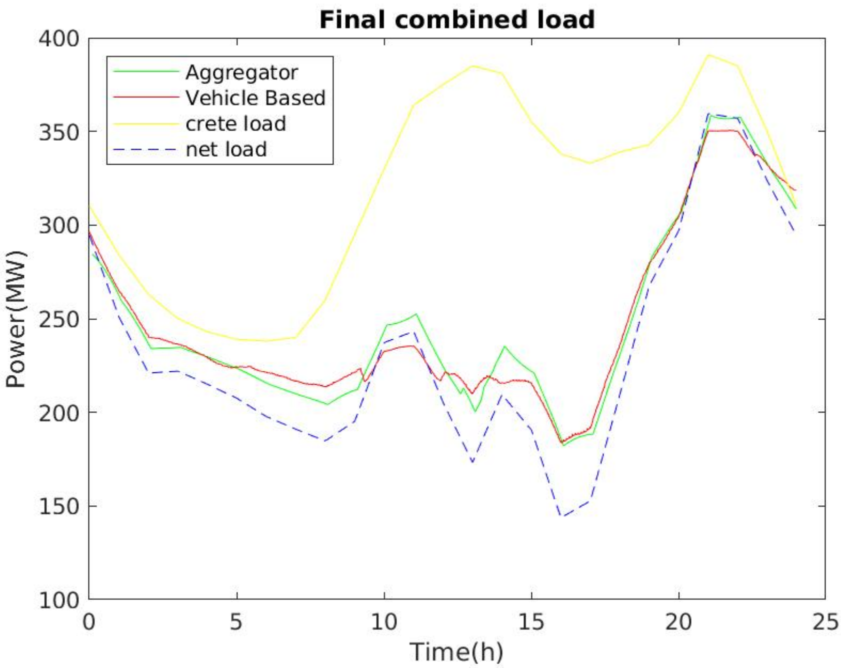

Figure 5.29. Total load with and without EVs: Low scenario (V2G Charging)

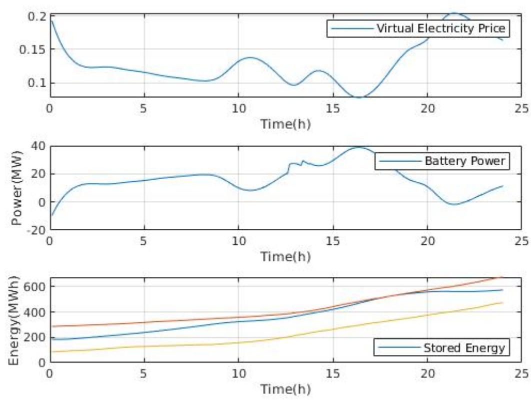

Figure 5.30. The Power generated by RES, the power of the aggregated battery and the total amount of Energy in a day: Low scenario (V2G)

5.7.2 Medium EV penetration scenario modeling results

5.7.2.1 Dumb Charging

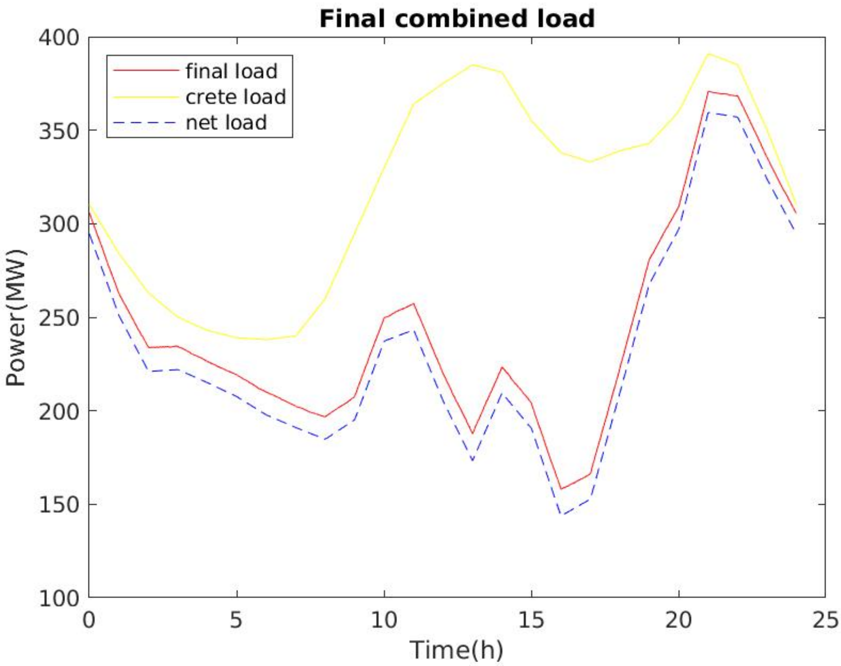

Figure 5.31. Total load with and without EVs: Medium scenario (Dumb Charging)

During Dumb Charging the vehicles draw from the grid a stable amount of Power for the duration of charging. In this scenario the total amount of vehicles is 74.768 EVs and the Power drawn in peak hours (15:00) reaches 27 MW. In this scenario as can be seen by the graph in Figure 5.28 the EVs can be powered exclusively from RES since the final load (net load + EV load) is under the original Crete load (which has the RES included, contradictory to the net load).

5.7.2.2 Vehicle Based Smart/Optimal Charging

During Smart Charging the vehicles adjusts the power drawn from the grid, in relation to the net load the island has. That way the vehicle can give power back to the grid when it deems that the grid is pushed. In this scenario the total amount of vehicles is 74.768 EVs and the Power drawn in peak hours (15:00) reaches 27 MW. In this scenario as can be seen by the graph in Figure 5.32 the EVs cannot be powered exclusively from RES since the final load (net load + EV load) is over the original

Crete load (which has the RES included, contradictory to the net load) in some cases. But this is not the main benefit of this method, since it can be seen that it tends to normalize and flatten the load of Crete.

5.7.2.3 Aggregator Controlled Charging

Using the V2G Charging method the EVs have the ability to return power back to the grid when necessary. In this method of changing the Aggregator determines when the vehicles will charge or discharge with the goal of maximizing the use of RES produced energy in the grid of Crete for 24 hours. By comparing the graphs in Figures 5.31, 5.32 it is observed that the Load graph as formed using the Aggregator method more closely resembles the net load one, with it giving power back to the grid when most necessary (e.g. around 21:30). In Figure 5.33 the power drawn by EVs follows the graph above when inverted, which shows the Virtual Electicity Price (which is the Net Load normalized). This means that when the Net Load (Load of Crete with RES substracted) is high, the power demand of the EVs is low. During unproductive hours for RES the power demand lessens comparing to the other methods. (i.e. around 02:00) In addition the EV power demand is higher during productive hours for RES (i.e around 15:00)

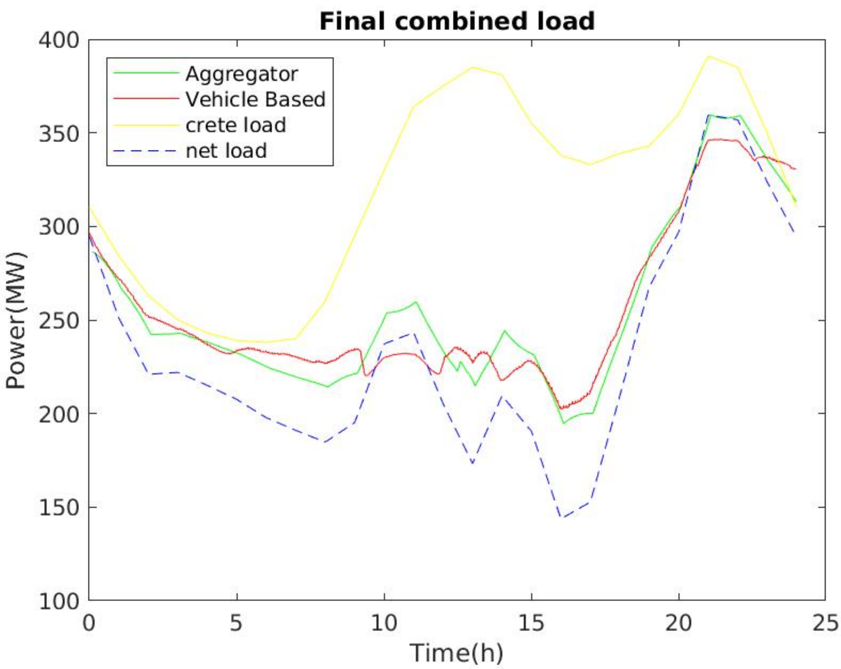

Figure 5.32. Total load with and without EVs: Medium scenario (V2G Charging)

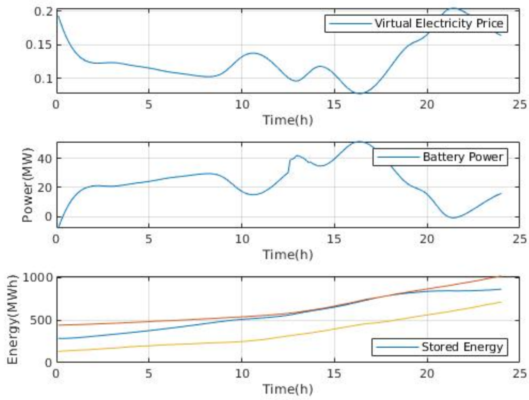

Figure 5.33. The Power generated by RES, the power of the aggregated battery and the total amount of Energy in a day: Medium scenario (V2G)

5.7.2.4 Comparison

In this Scenario when comparing the two methods (*Vehicle Based Smart/Optimal Charging* and *Aggregator Controlled Charging*) it is apparent that the are no longer that close to each other. Here with the *Vehicle Based Smart/Optimal Charging* method, the final load graph seems to have more small peaks and valleys, but still manages to be quite straight, so it is beneficial to the grid.The peaks and valleys are generated, because each vehicle calculates on its own when it should draw or give power from and to the grid. From the other hand the *Aggregator Controlled Charging* load continues to follow the curvature of the net load, in the most part (while being smoother when compared to lower penetration scenarios), while mostly emphasizing drawing power when the net load is at its lowest, and it gives back to the grid, while the net load is at its highest.

Here it is apparent that while the *Aggregator Controlled Charging* method is not that smooth, the EVs can be powered exclusively by using RES while the other method is also able to achieve this. Moreover, the load generated by using the *Vehicle Based Smart/Optimal Charging* method is even smoother, when comparing it to the same penetration scenario, but with fewer RES.

5.7.3 High EV penetration scenario modeling results

5.7.3.1 Dumb Charging

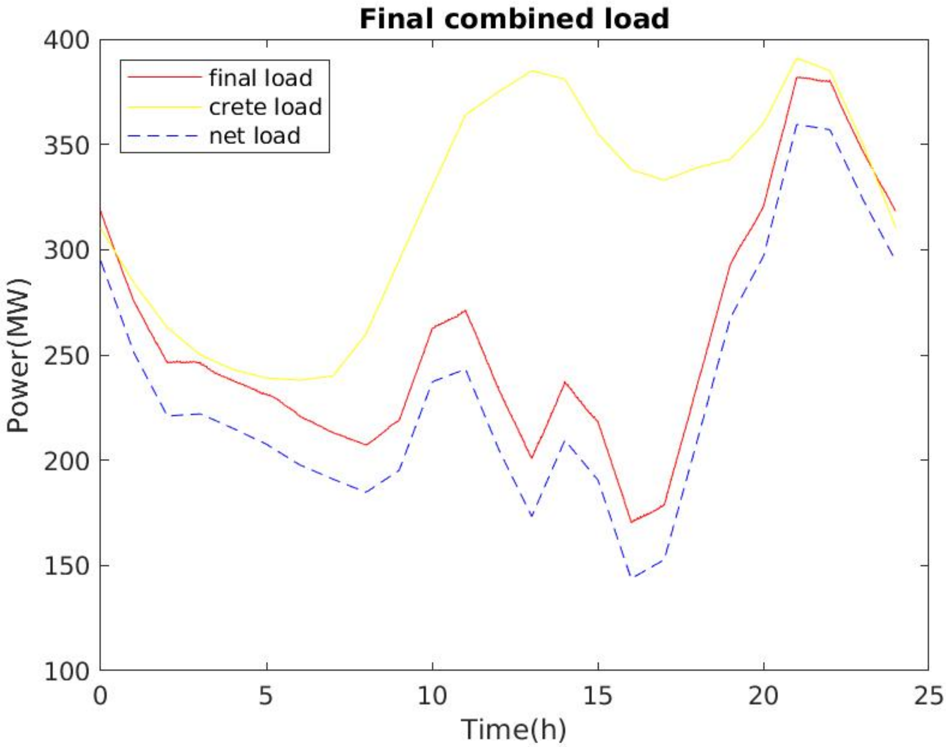

Figure 5.34. Total load with and without EVs: High scenario (Dumb Charging)

During Dumb Charging the vehicles draw from the grid a stable amount of Power for the duration of charging. In this scenario the total amount of vehicles is 149.536 EVs and the Power drawn in peak hours (15:00) reaches 54 MW. In this scenario as can be seen by the graph in Figure 5.34 the EVs can lamost be powered from RES since the final load (net load + EV load) is over the original Crete load (which has the RES included, contradictory to the net load), only for a small amount of time during the day.

5.7.3.2 Vehicle Based Smart/Optimal Charging

During Smart Charging the vehicles adjusts the power drawn from the grid, in relation to the net load the island has. That way the vehicle can give power back to the grid

when it deems that the grid is pushed. In this scenario the total amount of vehicles is 149.536 EVs and the Power drawn in peak hours (15:00) reaches 54 MW. In this scenario as can be seen by the graph in Figure 5.35 the EVs cannot be powered from RES since the final load (net load + EV load) is over the original Crete load (which has the RES included, contradictory to the net load). Here with a higher volume of vehicles, the benefits of this method tend to lessen, since the load is not flat or even close to it. This is happening because each EV acts independenty and all the vehicles give power back to the grid or even preffer to lessen the power drawn at the same periods of the day.

5.7.3.3 Aggregator Controlled Charging

Using the V2G Charging method the EVs have the ability to return power back to the grid when necessary. In this method of changing the Aggregator determines when the vehicles will charge or discharge with the goal of maximizing the use of RES produced energy in the grid of Crete for 24 hours. By comparing the graphs in Figures 5.34, 5.35 it is observed that the Load graph as formed using the Aggregator method resembles the net load one, while being smoother overall.

In Figure 5.36 the power drawn by EVs follows the graph above when inverted, which shows the Virtual Electicity Price (which is the Net Load normalized). This means that when the Net Load (Load of Crete with RES substracted) is high, the power demand of the EVs is low. During unproductive hours for RES the power demand lessens comparing to the other methods. (i.e. around 02:00) In addition the EV power demand is higher during productive hours for RES (i.e around 15:00)

5.7.3.4 Comparison

In this Scenario when comparing the two methods (*Vehicle Based Smart/Optimal Charging* and *Aggregator Controlled Charging*) it is apparent that the are now completely different from each other, since the first now resembles and inverted netload. Here with the *Vehicle Based Smart/Optimal Charging* method, the final load graph seems to have high peaks and valleys, deeming it no longer beneficial to the grid. The peaks and valleys are generated, because each vehicle calculates on its own when it should draw or give power from and to the grid. On the other hand the *Aggregator Controlled Charging* load no longer continues to follow the curvature of the net load, but manages to become a lot smoother when compared to lower penetration scenarios. In this scenario we are beginig to see the benefits of the Aggregator model, since it starts to be a lot smoother, which is very beneficial to the grid. In higher EV penetration scenarios, even the greater production of RES Energy is not sufficient to make the *Vehicle Based Smart/Optimal Charging* method viable, since it has high peaks and deep valleys in the final load.

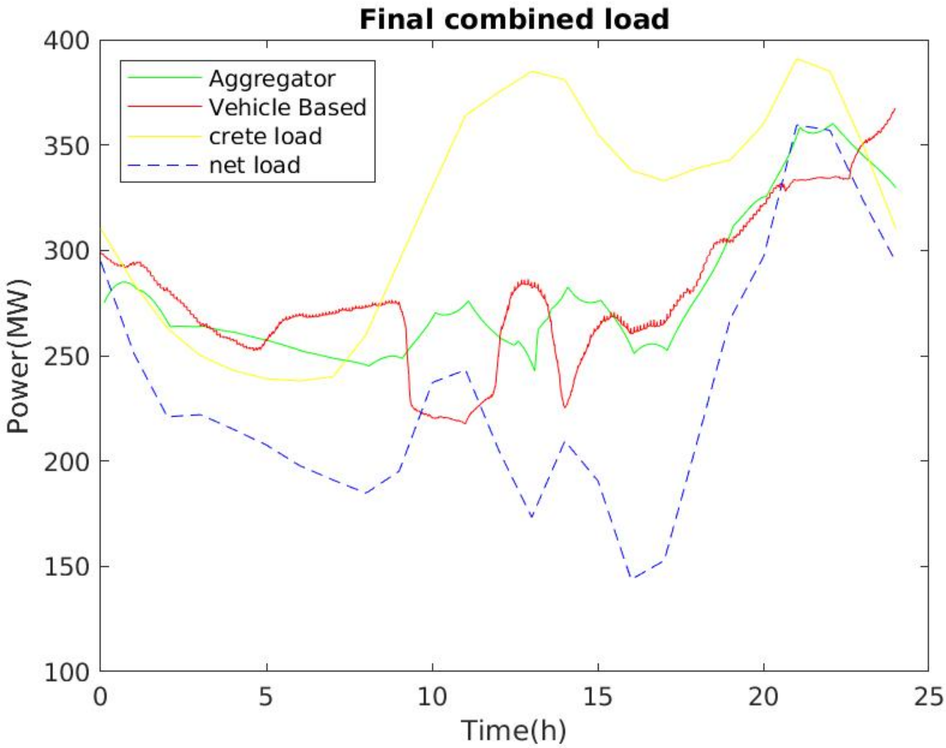

Figure 5.35. Total load with and without EVs: High scenario (V2G Charging)

5.7.4 Ultra High EV penetration scenario modeling results

5.7.4.1 Dumb Charging

During Dumb Charging the vehicles draw from the grid a stable amount of Power for the duration of charging. In this scenario the total amount of vehicles is 224.304 EVs and the Power drawn in peak hours (15:00) reaches 81 MW. In this scenario as can be seen by the graph in Figure 5.37 the EVs cannot be powered from RES since the final load (net load + EV load) is over the original Crete load (which has the RES included, contradictory to the net load). This can be seen mostly in the majority of the graph, but is examplified during low RES production.

5.7.4.2 Vehicle Based Smart/Optimal Charging

During Smart Charging the vehicles adjusts the power drawn from the grid, in relation to the net load the island has. That way the vehicle can give power back to the grid when it deems that the grid is pushed. In this scenario the total amount of vehicles

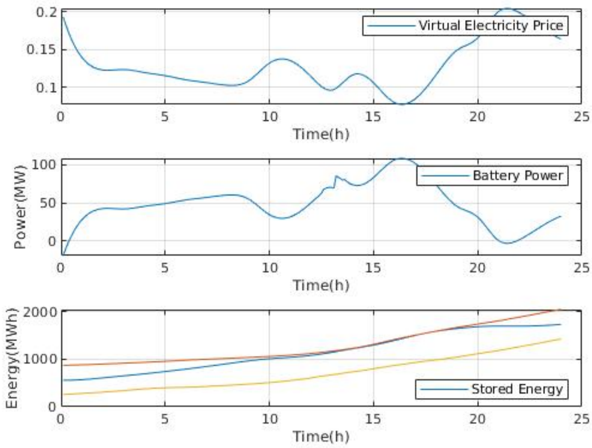

Figure 5.36. The Power generated by RES, the power of the aggregated battery and the total amount of Energy in a day: High scenario (V2G)

is 224.304 EVs and the Power drawn in peak hours (15:00) reaches 81 MW. In this scenario as can be seen by the graph in Figure **??** the EVs cannot be powered from RES since the final load (net load + EV load) is over the original Crete load (which has the RES included, contradictory to the net load). Here with a higher volume of vehicles, the benefits of this method tend to lessen, since the load is not flat or even close to it. This is happening because each EV acts independenty and all the vehicles give power back to the grid or even preffer to lessen the power drawn at the same periods of the day. In this scenario the sideffects of the Smart Charging method are examplified.

5.7.4.3 Aggregator Controlled Charging

Using the V2G Charging method the EVs have the ability to return power back to the grid when necessary. In this method of changing the Aggregator determines when the vehicles will charge or discharge with the goal of maximizing the use of RES produced energy in the grid of Crete for 24 hours. By comparing the graphs in Figures 5.37, 5.38 it is observed that the Load graph as formed using the Aggregator method is now almost smooth and straight.

In Figure 5.39 the power drawn by EVs follows the graph above when inverted, which shows the Virtual Electicity Price (which is the Net Load normalized). This means that when the Net Load (Load of Crete with RES substracted) is high, the power demand of the EVs is low. During unproductive hours for RES the power demand lessens comparing to the other methods. (i.e. around 02:00) In addition the EV power demand is higher during productive hours for RES (i.e around 15:00)

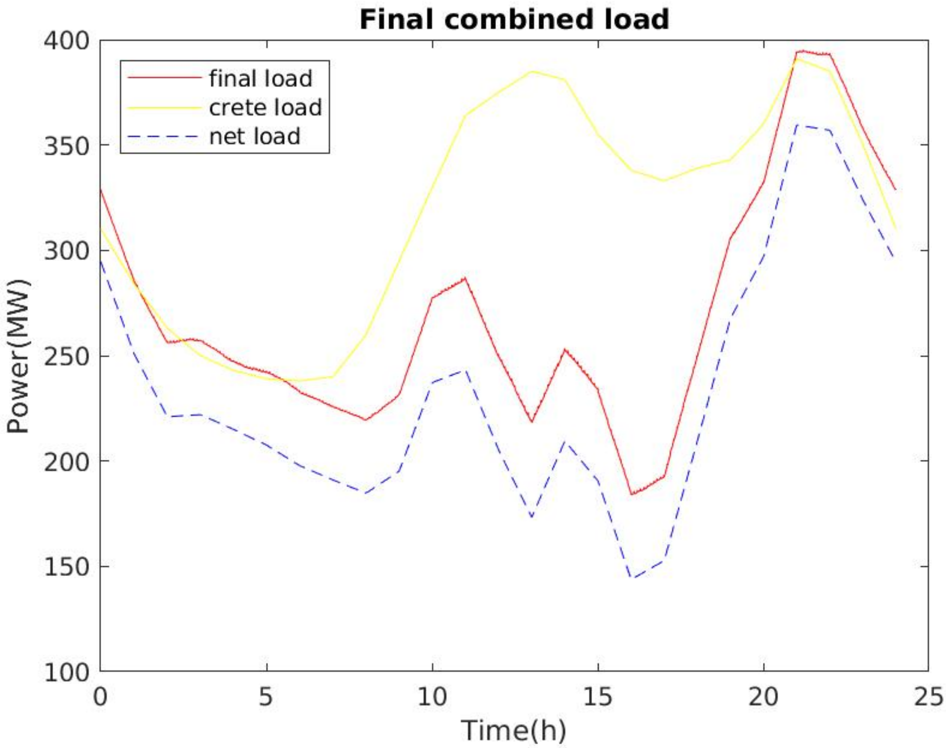

Figure 5.37. Total load with and without EVs: Ultra High scenario (Dumb Charging)

5.7.4.4 Comparison

In this Scenario when comparing the two methods (*Vehicle Based Smart/Optimal Charging* and *Aggregator Controlled Charging*) it is apparent that the are now completely different from each other, since the first now resembles and inverted and examplified netload. Here with the *Vehicle Based Smart/Optimal Charging* method, the final load graph seems to have very high peaks and valleys, deeming it no longer beneficial to the grid. The peaks and valleys are generated, because each vehicle calculates on its own when it should draw or give power from and to the grid. On the other hand the *Aggregator Controlled Charging* load is a lot smoother when compared to lower penetration scenarios.

In very high EV penetration scenarios, even the greater production of RES Energy is not sufficient to make the *Vehicle Based Smart/Optimal Charging* method viable, since it has very high peaks and deep valleys in the final load.

In this scenario we see the benefits of the Aggregator model, since it starts to be a lot smoother, which is very beneficial to the grid. So it can be concluded that the Aggregator Controlled Charging performs better on higher EV penetration scenarios,

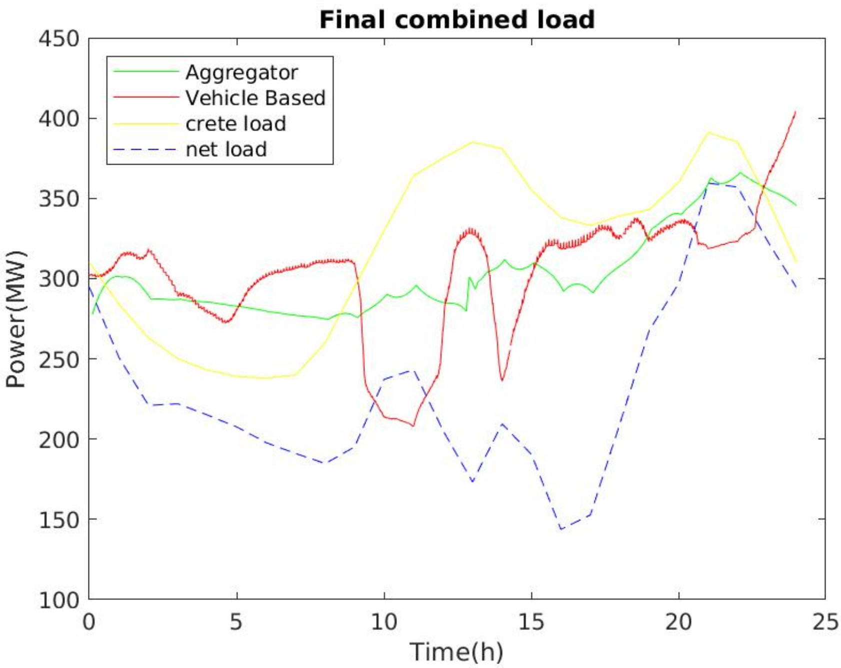

Figure 5.38. Total load with and without EVs: Ultra High scenario (V2G Charging)

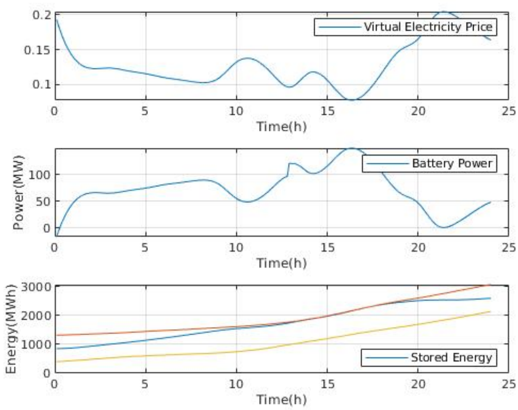

Figure 5.39. The Power generated by RES, the power of the aggregated battery and the total amount of Energy in a day: Ultra High scenario (V2G)

while the Vehicle Based Smart/Optimal Charging is better when the EV penetration is lower, but in this case with a high RES Production, the initial drawbacks of *Aggregator Controlled Charging* seem to lessen even more, while getting even better at high EV penetration scenarios when compared to the previous cases of lower RES production. This makes it a safer and more reliable option, especially in high RES production cases.

Conclusion

In this thesis, the routes and charging of electric vehicles were modeled for the various scenarios of their penetration into the Electricity System of Crete. The primary objective was to optimize the use of renewable energy sources and to smooth the daily load curve of Crete.

More specifically, it was initially put into place to determine each vehicle's routes for all penetration scenarios. To make the results as realistic as possible, actual data for the island of Crete were used to represent travel distances, travel times, and charging times.

Then, using the entire fleet as one equivalent battery with cumulative power and energy for every second, the aggregator model was put into place, which controls the charging and discharging of all electric vehicles for each moment. The aggregator model was incorporated into the Crete grid so that it could manage the fleet of vehicles for the entire 24 hours and choose when to charge and discharge their batteries based on the demands of the grid and the energy produced by renewable energy sources.

As is evident from the results, the optimization of the load of Crete, regarding the renewable energy sources was achieved, since there is a significant reduction in the overall power needed by comparing to Dumb and convensional Smart Charging. In addition the initial net profile appeares to affect the load of Crete with an increase in load demand at the points of highest RES production and a decrease in demand in opposite periods. In high scenarios the load demands of the EV fleet ceases to get completely fulfilled by renewable energy sources, but manages to keep a low overall cost. When expanding the renewable energy sources of the island it is apparent that the load demand tends to be fulfilled, while still lacking in extremely high EV penetration scenarios.

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