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Buffering PV Output During Cloud Transients with Energy Storage

Yacouba Moumouni
University of Nevada, Las Vegas, yacoubam@unlv.nevada.edu

BUFFERING PV OUTPUT DURING CLOUD TRANSIENTS WITH ENERGY STORAGE

By

Yacouba Moumouni

Bachelor of Engineering
Electrical and Computer Engineering
Federal University of Technology, Minna, Nigeria
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Howard R. Hughes College of Engineering
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Department of Mechanical Engineering

- Robert Boehm, Ph.D Committee Chair
- Woosoon Yim, Ph.D Committee Member
- Yitung Chen, Ph.D Committee Member
- Yahia Baghzouz, Ph.D Graduate College Representative
- Ronald Smith, Ph. D., Vice President for Research and Graduate Studies and Dean of the Graduate College

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ABSTRACT

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by

Yacouba Moumouni

Dr. Robert Boehm, Examination Committee Chair

Professor of Department of Mechanical Engineering

University of Nevada, Las Vegas (UNLV)

Consideration of the use of the major types of energy storage is attempted in this thesis in order to mitigate the effects of power output transients associated with grid-tied CPV systems due to fast-moving cloud coverage. The approach presented here is to buffer intermittency of CPV output power with an energy storage device (used batteries) purchased cheaply from EV owners or battery leasers. When the CPV is connected to the grid with the proper energy storage, the main goal is to smooth out the intermittent solar power and fluctuant load of the grid with a convenient control strategy. This thesis provides a detailed analysis with appropriate Matlab codes to put onto the grid during the day time a constant amount of power on one hand and on the other, shift the less valuable off-peak electricity to the on-peak time, i.e. between 1pm to 7pm, where the electricity price is much better. In this study, a range of base constant power levels were assumed including 15kW, 20kW, 21kW, 22kW, 23kW, 24kW and 25kW. The hypothesis based on an iterative solution was that the capacity of the battery was increased by steps of 5 while the base supply was decreased by the same step size until satisfactorily results were achieved. Hence, it turned out with the chosen battery capacity of 54kWh coupled to the data from the Amonix CPV 7700 unit for Las Vegas for a 3-month period, it was found that 20kW was the largest constant load the system can supply uninterruptedly to the utility company. Simulated results are presented to show the feasibility of the proposed scheme.

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INTRODUCTION

Variability is perceived to be a major negative issue for the proliferation of large-scale PV systems. The sudden changes in PV power output during cloudy weather conditions are the primary concern. Unlike solar thermal electric systems, which have natural thermal inertia that damps out sudden changes, PV system output responds instantaneously to changes in sunlight. As a result, operating PV systems have demonstrated the potential for substantial ramps during partially cloudy days. Under certain weather conditions, PV installations can change output by ±70% in a 30 to 90 second time frame, many times per day. Hence, it has been speculated that PV fields could have large and frequent ramp events that may create challenges for electric grid operators. The impact of clouds on the variability PV system power generation depends on the system size, the shape, size, transparency, speed and direction of movement of the cloud. A small system can be completely covered by a cloud, thus drastically reducing its power output. On the other hand, in a large-scale PV plant that covers a sufficiently large area, some parts of the plant may be shaded for a period of time while other parts of the plant aren't and will continue to produce power. Similar to wind farms, the geographic diversity is known to dampen the total power variability of large PV systems. The aforementioned problems constitute a major drawback to the penetration of PV plants to the grid and a sort of complete denial by the utility companies of the outweighing beneficial role they can play in supporting our economy. Therefore, the purpose of this study is to mitigate those problems by analyzing an Amonix 7700 HCPV system with use of a bolt-on battery system. For the sake of simplicity, the battery size will initially be treated as a parameter until the affordable constant load is reached. As a matter of fact, a win-win trade-off would automatically be established between the utility companies and the HCPV plant owners in terms of price per kWh of renewable electricity sold.

CHAPTER 1

1.1 Overview of CPV

CPV technology was developed with the sole motivation to gain high efficiency and maximum power output from the minimum possible area of modules. Another purpose, but economical, was to generate inexpensive electricity from PV panels. The whole concept of CPV is based on the French physicist's A. Fresnel discovery that has to do with the optical lens. The sun light is simply focused through a Fresnel lens onto the solar cells which are made up of the combination of elements belonging to columns III and V, Table **1**. Nonetheless, the small size of those cells has nothing to do with their efficiency. In other words, they are incredibly highly efficient.

The idea behind using the Fresnel lenses is their cost effectiveness, because they are made out of plastic material. Their use with the newly developed three junction cells' technology results in high power conversion rates. The system of light concentration between the concentrator (the collector/lens) and the converter (receiver/cells) is about a ratio of several hundred times.

The tandem or triple junction cells were initially used specifically for space application and were mainly InGaP, InGaAs or Ge. Nowadays however, multijunctions cells are used for terrestrial with concentrating system applications also, not only because of the reasons mentioned earlier such as plastic lenses, but also because of the manufacturers' determination in making it affordable by reducing the expensive cells' area. In some countries, how land is being used is becoming a serious matter because the space is so limited. Hence, in situations like that, the efficiency of the PV is crucial matter and is highly advisable that not only a little piece of land, but also a tiny piece of technology should generate a much power as possible.

Table 1 Periodic table of column III and V semiconductor elements

S/N	Column III	Column V
1	**B**	**N**
2	**Al**	**P**
3	**Ga**	**As**
4	**In**	**Sb**
5	**Ti**	**Bi**

1.2 Theory of Multijunction/Tandem Cells

The single junction PV cell is by far the most commonly used technology ever to generate electricity from the sun by creating an electric field within pn semiconductor material. One great disadvantage of using the single junction is that only a portion of sunlight can free an electron. In other words, any photon of light for it to be able to do so, should have energy greater or equal to that of the gap between the valence and the conduction bands of the material ($h\upsilon \geq Eg$). Therefore, the sun's spectrum is poorly utilized and is only limited to part of it which carries energy greater than the forbidden band. Hence, the photovoltaic effect of a single junction is purely shrunk and narrowed to the higher energy photons.

When there is a problem, there is always a solution. Hence, multiple junctions are packed one on top of the other in order to get around this limitation of the single junction. Those different junctions have different band gap energies in order to respond differently to the solar spectrum as illustrated in Figure **1**. This technology is known as tandem cells or multijunction and can achieve higher efficiency by converting more of the sun's spectrum into electricity.

Below, a stack of individual single-junction cells is shown in descending order of band gap (Eg) that makes up a multijunction device. The top cell captures the high-energy photons and passes the rest of the photons on to be absorbed by lower-band-gap cells.

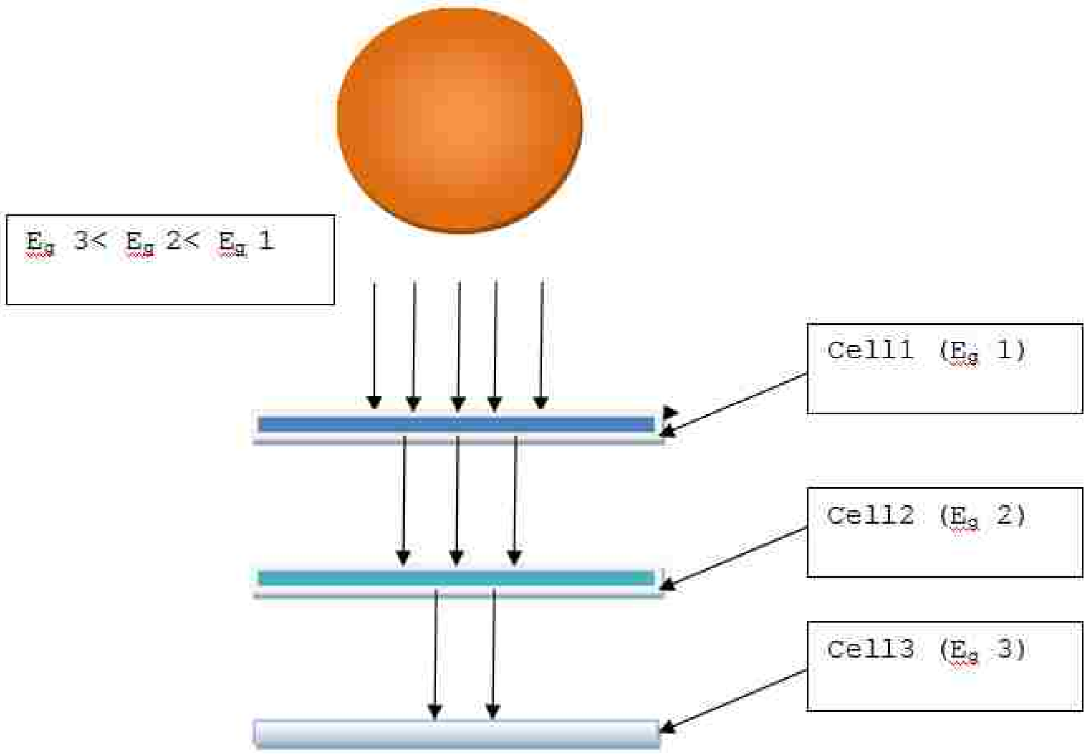

Figure 1 Structure of a tandem cell

1.3 CPV 7700

As opposed to flat-plate PV modules, in CPV, either cheap optical mirrors or plastic lenses are used to harness the solar energy and to focus it onto the tiny cells. As a matter of fact, CPV technology differs quite a bit from that of flat-plate in various ways.

Firstly, they are highly efficient due to the triple junctions' designs they use. Secondly, the mirrors and lenses they use, are of great advantage compared to the traditional flat-plate technology. As semiconducting materials are becoming more and more expensive as they are becoming more and more pure in terms of quality, there is a significant need for using less material in the chip design. With regard to that, Amonix was able to shrink the area of the solar cells by using less semiconductor material associated with energy efficient optics into its design. Therefore, CPV has its output power tremendously increased at the expense of not only cutting down the number of cells, but also their size. Figure **2** below shows the optics behind a CPV for a unit cell.

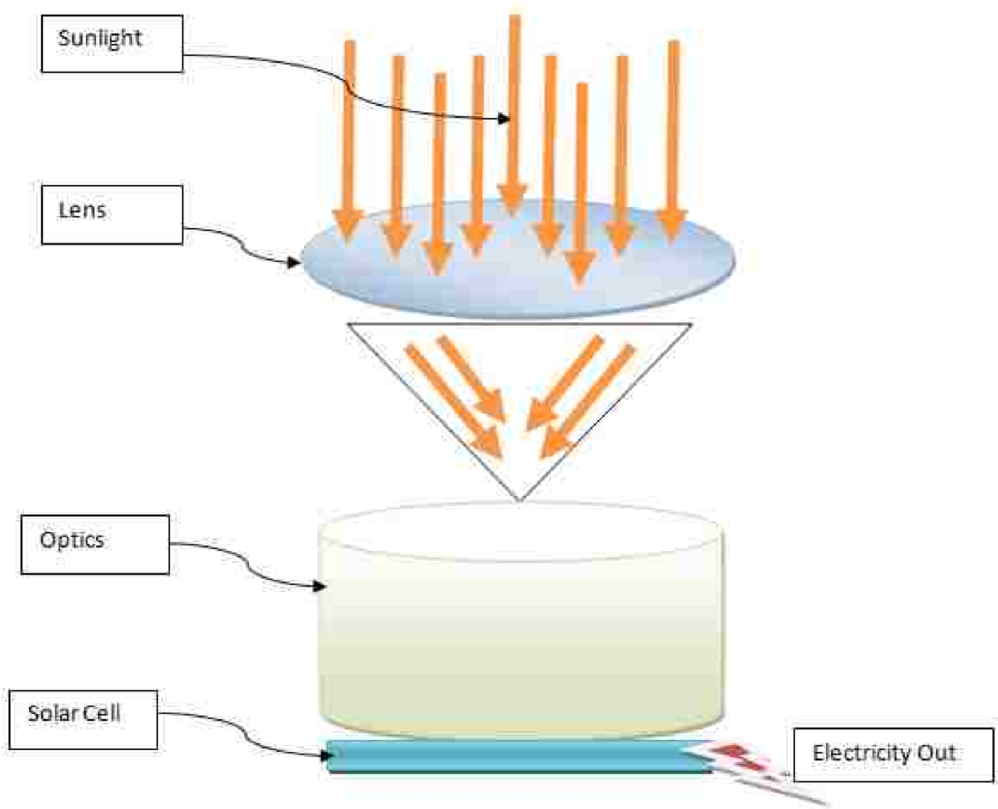

Figure 2 The optics of CPV

1.4 Characteristics of the Amonix CPV 7700

As the Amonix CPV 7700 (see Figure 3) is the focus of this thesis, it is worth noting that this technology utilizes dual-axis tracking systems and that one single unit is comprised of seven Mega modules. The efficiency of the Amonix CPV 7700 is by far greater than conventional panels, allowing it to generate over 40% more energy [3]. The unit is easy to install and easy to disassemble, making it cost effective with respect to renewable energy standards. The overall efficiency delivered to the grid is in excess of 29% due to some losses whereas at the module level, it is 31% and 40% at the cell level. This technology (see Table 2 for the characteristics) has proven to be cost-effective, environmentally friendly by producing clean energy and is capable to generate power on a large scale for use by electric utilities.

Table 2 Characteristics of the Amonix CPV 7700 under specific STC [3]

Performance	
Name plate capacity (AC)	53kW (+/- 5%)
Observed system efficiency (Post inverter)	25%
Power factor	>98%
Operating voltage (AC, 3-Phase)	480V
Power Temperature coefficient	-0.16%/K
Physical	
Overall dimensions	72ft(w)x49ft(h)
Max height	50.5ft
Min ground clearance	2ft
Pedestal diameter	3ft
Foundation depth	18ft
Tracking type	2-Axis
Drive type	Hydraulic
Sun tracking method	Closed loop sun seeker
MegaModule Warranties	
Limited product warranty	5 years
10 year power output	92%
20 year power output	84%
Environmental	
Max. operating wind speed	28 Mph
Max. wind loading (ASCE 7-05, category C)	90 Mph
Time to wind stow position	<1 Min
Operating Temperature range	$-10^{o}C$ to $+50^{o}C$
Designed lifetime	>25years
Hydraulic fluid	Biodegradable
Land required per MW	4 to 6 Acres

The Amonix units have their own testing conditions, viz. DNI 850W/m^2; temperature 20°C; wind velocity 1m/sec (at 10m height).

Although the Amonix CPV 7700 is economical, the acrylic Fresnel lenses it uses collect and concentrate sunlight up to 500 times onto the small, but highly efficient solar cells as opposed the conventional PV. The lenses are affixed to the top of a 10' x 49' rectangular steel frame, with 30 photovoltaic solar cells mounted onto each of the receiver plates beneath the lenses.

Each Amonix Mega Module contains 36 such sets of lenses and corresponding receiver plates, producing ~10 kW (DC) of concentrated solar power [3].

Figure 3 CER, UNLV - CPV 7700

As mentioned earlier, the dual-axis tracker's sole purpose is to constantly keep the cells perpendicular to the incoming sunlight in order to be able to capture the direct beam. Otherwise, the optics used in the CPV will not function properly as they cannot capture beams other than direct radiation such as diffuse or ground reflected beams. Ultimately, if the optics fails to respond properly to sunlight, the direct consequence is that the cells output electricity will be decreased and the overall efficiency will definitely be lower than it could be.

1.5 The importance of renewable energy (Solar)

In the last decade, the GHG emissions such as CO_2 and methane (CH_4) have been globally a serious issue. By virtue of that, a new concept known as “Trilemma” came into play due to the difficulties associated with the reduction of the amount of CO_2 in the atmosphere. This concept involves the economy, the environment and the energy sector as well whereby it is difficult to choose one of them as each of which is unfavorable or unacceptable and carry the same weight [14]. In [24], it is described as an impossible triangle. Figure **4** below is the perfect illustration.

The human population on the other hand is more than 6.7 billion people [14] and all of us aspire to have a sustained life with the appropriate energy required. The society as whole needs to figure out not only the appropriate resources to meet these aspirations, but also needs to quantify the required resources for the benefit of the present and the future generations. It is stated in 0 that in the third world, significant attempts to boost the energy per capita use are underway.

The worldwide consumption of the fossil fuel turns out to be a destructive and irreversible phenomenon on earth. Predictions showed that the fossil energies will gradually reach their end since they are non-renewable and are quite finite and this could lead to a tremendous catastrophe for the entire planet. Despite that fact, most of the industrialized countries such as USA, France and UK rely on nuclear and fossil fuels to meet their respective energy demands. Instead of diversifying their energy sources for their national security purposes, future generations are condemned to be borne in such a harsh environment that lacks energy independency. In other words, newly discovered diseases are now commonplace including breathing problems, skin cancer etc, due to clean water and clean air issues. Therefore, the Earth's climate is under constant change.

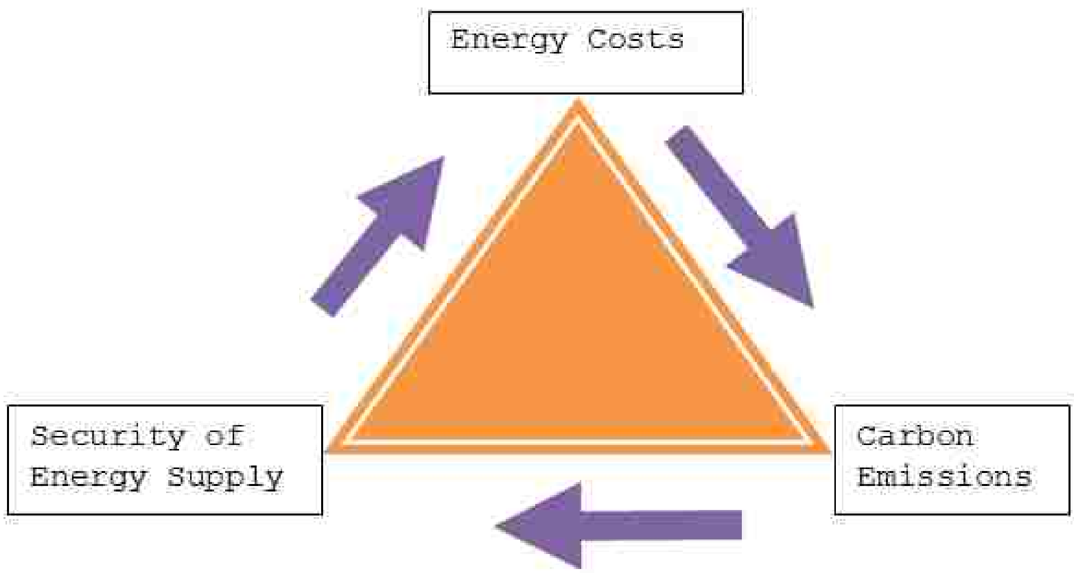

Figure 4 The energy trilemma

The inhabitants of the planet Earth are fortunate enough to have in their energy midst other new and renewable sources that cannot be depleted on the human time scale such as solar, wind, and geothermal, to mention but few that are undoubtedly capable of meeting our daily energy needs. Therefore, pushing towards them will surely help to alleviate some if not all the above mentioned problems and at the same time provide important benefits. The understanding and the development of these renewable energies can solve many of our current issues, viz.:

- Natural resources conservation for the future generation

- Diversification of fuel and energy mix through the creation of new and sustainable competitions in order to keep constant fuel price
- Creation of new jobs which will result in an economic development
- Improvement of the energy security
- Present and future regulations compliance cost will be reduced
- Cutting down of the reliance on imported oil and electricity and insulation of the economies from oil price spikes
- Environmental and public health protection by cutting down the GHG emissions that are responsible for:
    - Global warming
    - Acid rain
    - Thermal pollution
    - Water
    - Air pollution [14], etc.

CHAPTER 2

2.1 Problems associated with sunlight transients

The PV power generation is intermittent by nature as depicted in Figure 6 shown at the end of this section. When PV power plants are connected to our electric grid at a high level, certain precise and prior actions were to be met such as economical and reliable storage system. The latter would certainly allow the utility companies to eliminate the spinning that serves as back-up utility generation with the sole purpose to offset the intermittency of PV. The same plot in Figure 6 shows the output power output of the CER (CPV 7700) unit located at UNLV over the course of a day with frequent passing clouds. The magnitude as well as the rate of change of the power appear to be significant in a short period of time. This is to say that the output power can swing back and forth in seconds as described in [2] from 20% or less and back again. With this intermittency pattern, mere high penetration of PV to the grid will be more than devastating. The utility operations can seriously damage the load-side sensitive appliances as a result of voltage and power factor oscillations. Clearly stated, at certain point of the utility management, any significant variation, be it frequency, voltage or power factor angle will never be tolerated because the outcome may be disastrous.

The management of most the power companies that have part of their power generated by grid-connected solar PV faces a serious challenge. Though there are a large and diverse number of electricity consumers, the power systems are mainly designed to satisfy at all the time and by all means the aggregated electricity demand. That particular electricity demand is dynamic throughout the modern era of humanity. In other words, it is viewed as a function of the time of the day, the weather, the seasons of the year and the business pattern. In the same manner, the shape of the load over time and the amount of electricity consumed are all variable due to the factors mentioned above [6]. That negative fact can lead to discrepancy between the aggregate electrical production and the aggregate energy consumption, which may appear as a frequency variation.

On the other hand, as the demand increases, the power system will end up being in a critical situation which has devastating consequences. The latter could be a deficit in reactive power which is the same as voltage reduction and when the voltage falls under a certain threshold point by becoming smaller and smaller, a voltage collapse or avalanche is inevitable [35]. Obviously, the largest challenge of solar power plants is their intermittency followed by the ability of the electric grid to accommodate it in the smartest manner.

Fortunately as time passes by, a huge variety of options have evolved in order to tackle this issue, where the most common ones are basically system designs, load forecasting, smart grid and energy storage. The latter is the topic of concern in this thesis. Solar electricity based generation (PV, CPV) is mainly dependent on the amount of sunlight that hits the conversion device at a point of time in a given location. The power output of the device varies throughout the day and the seasons, as it is affected by factors such as the cloud coverage and other harsh weather conditions (See Figure **5**). Therefore, regardless of many or few solar power plants penetrating the grid, the power companies (operators) can still manage the variations in one of the aforementioned ways. In short, people are not very familiar with the concept of intermittency of solar sources and how challenging it could be to the renewable energy industry as a whole.

Figure 5 CPV 7500 Cloudy weather, NREL

Based on the knowledge of the planet Earth's revolution around the Sun and onto itself, solar power plants transform the solar energy at the best of their efficiencies and deliver to the utility companies their maximum output in either kilowatts, megawatts or gigawatts depending on the system type. Due to the aforementioned rotation of the Earth and the seasonal angle variation of the Sun, which changes constantly over the course of the year, the PV output power varies significantly. Additionally, some mismatches created by physical objects such as dust, tree leaves or clouds contribute to substantially worsen the situation.

Solar is undoubtedly one of the cleanest energies, but primarily its inherently intermittent nature lead most of the time to power production issues such as network quality and stability. Thus, the larger the penetration of renewable (solar), the greater the fluctuations it poses and the larger the problems that have to do with transmission. Another serious problem associated with solar power generation is that of the huge distance between the best solar sites and the load centers such as highly populated urban zones. Inevitably, the ability to comprehend thoroughly the energy storage associated with the proper control is essentially the way out as more intermittent abundant and renewable power is brought into operation nowadays. In essence, the control system should incorporate dynamic reactive power compensators in order to instantly respond to frequent signal variations which result in either voltage or frequency stability issues. On the other hand, the amount of power carried by a transmission line is totally dependent on the types of pylons and the size of wires allotted for that particular purpose. Likewise, electrical devices can malfunction when the transmission power line voltage is too small and resulting in a further voltage drop below the minimum accepted level. Nonetheless, the opposite of that, i.e. too much electricity can cause surges that can potentially damage the devices or in the worst case scenario can trigger the CBs by shutting off the power completely.

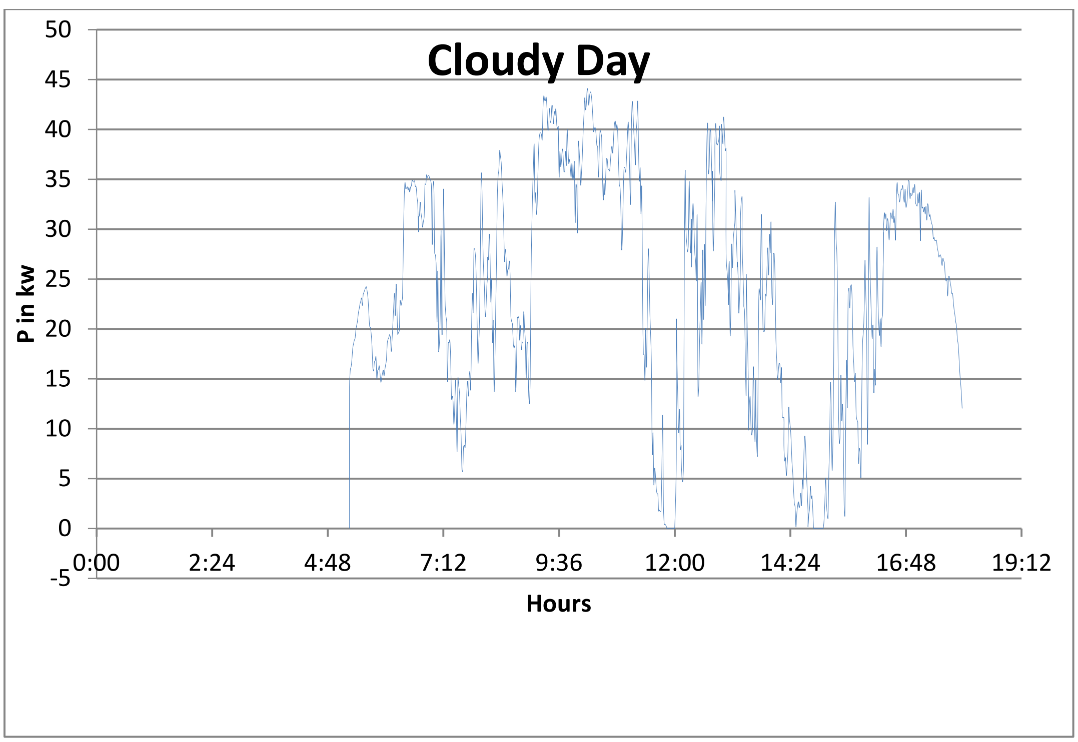

Figure 6 CPV 7700 output power of a cloudy day

Most severely, the intermittent problem of solar power generation can be consistently acute at the distribution level, i.e. residential zones for the utility companies. Another meaning is that the closer the individual solar power systems are to one another, the more significant will be the sum of each individual contribution on any spike in the flow of power, thus making it worse for utility management to control [7].

For a mere comparison purpose, as opposed to a typical cloudy day, a clear summer day plot of the CPV power output is quite different. It could look like the curve shown in Figure **7** below.

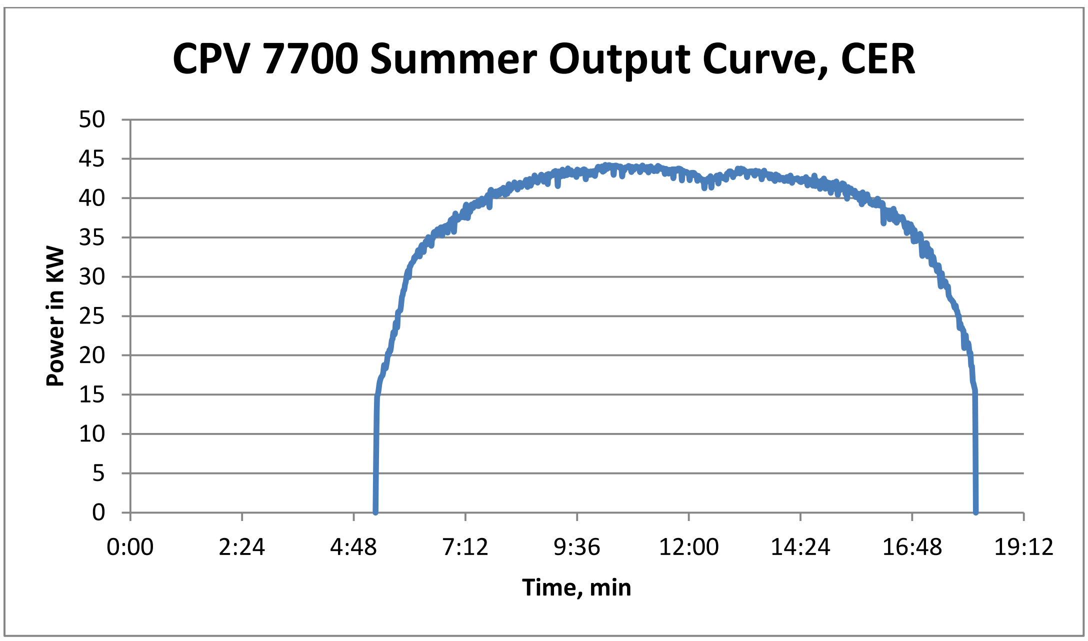

Figure 7 CPV 7700 output of a clear day

2.2 How to mitigate transient PV behavior

High PV penetration onto the grid has always been problematic in technical terms and because of that the utility management and the law makers are reluctant and yet to come up with the right legislations in favor of that.

Nevertheless, peak and intermediate loads are more and more satisfied by the use of PV with the sole provision of appropriate and additional backup energy storage units. The latter is intentionally utilized in order to be able to assure a continuous power supply in the late evening during the period of low PV generation [2].

The integration of a storage system has triple advantages, namely environmental, operational and financial to the society as a whole and to the power companies through load shaving. Things that were not possible before could easily be accomplished such as load shifting, peak shaving and demand response by storing any excess energy and supplying it to a load at some later time.

Transient output is basically a problem associated with the quality of the electric power especially at the distribution level with high penetration of PV onto the grid. In this regard, the output of the CPV in question depends on three factors: the solar irradiance, cloud coverage and its performance. So in a broad term, there could be two different ways to mitigate the transient of electric power, either from the consumers' side or the utility side. Details are found in [60]. The solution in concern in this thesis is to suppress or counteract the issues related to power intermittency through the installation of a backup ESS that could smooth out the ripples. Several ESS devices are examined in Chapter Three with emphasis on used EV batteries.

CHAPTER 3

3.1 Assessment of Energy Storage Technology

It is definitely not an easy task to find any single energy storage system that will fit all the applications. Each energy storage system has unique characteristics that make it fit into specific applications. The primary purpose of energy storage is to push away the limits of fixed demand trends of electricity by shifting the supply of PV power to a certain desired time schedule. Although sufficient energy storage is expensive, it can virtually help to shift any amount of power in contrast to power demand, proportional to their size without any limit. In a simplistic view, storing energy is the same as shifting electrical load and can reasonably make sense economically. Hence, the usefulness to PV and energy storage are strictly interrelated in two different ways [41], which are the absorption of the surplus power and the allowance of energy to be utilized at convenience, most of the time when it is not produced, or to suppress intermittencies. So, shifting one portion of the electrical load as done in [42] from peak time to off-peak has tremendous economic implications and will definitely contribute to lessen the total electricity burden on the society as whole. Hence, based on their broad applications in electrical power system, ESS can be categorized into:

- Bridging power
- Power quality and
- Energy management (load leveling) [54].

The last two fall into the scope of the present study. A further classification of the ESS would be based on the engineering approaches used and are as follows:

- Mechanical systems (pumped hydro, compressed air energy storage (CAES)),
- Electrical systems (capacitors and ultra-capacitors),
- Chemical systems (Lead-acid battery, Li-ion battery, NiCad battery).

3.2 Description of various energy storage systems

In the present study, only some of the ESS will be covered for simplicity purposes. Moreover, only a brief description will be attempted to all the above mentioned systems that are not strictly relevant to this topic.

3.2.1 Mechanical ESS

Among the most popular mechanical storage systems that are currently used, only two of them will be described briefly in this passage, namely the pumped hydro systems (PHS) and compressed air energy storage (CAES). It is worthy to mention that among those, PHS is the most widely used storage at a large-scale on power systems. According to [54] it could be used for load balancing or load shaving.

3.2.1.1 Pumped Hydro Systems, PHS

PHS works with the principle of the gravity. During off-peak hours where the electricity is less expensive, water is pumped up into the higher reservoir (see Figure 8). Then during peak time, a large volume of water is released to the lower reservoir to drive a turbine coupled to an alternator. The conceptual configuration of PHS is illustrated in Figure 8 below. The two reservoirs are vertically separated in a conventional PHS [54]. The PHS application in peak shaving would be to pump the water back again to the elevated reservoir [57]. The following factors viz. the amount of water (V), the height (h) and the conversion efficiency determine the energy (E) produced. The conversion efficiency is found in previous studies [57] to be between 65 to 80%. The equation is as follows:

$$E(kWh) = \frac{V(m^3) * h(m)}{367} \qquad 3.1$$

Like any major technology, PHS has its own disadvantage which is its unfriendliness with respect to the environment.

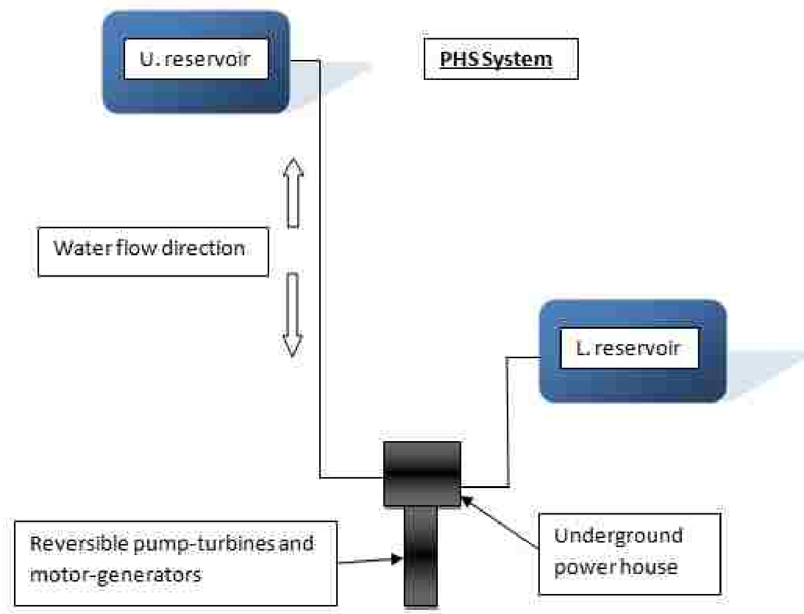

Figure 8 Configuration of PHS

3.2.1.2 Compressed Air Energy Storage, CAES

The second predominantly used mechanical ESS is the compressed air energy system (CAES). In a like manner, the low cost electricity of the off-peak period is used to supply a compressor and pump air into an underground cavern. Hence, during on-peak time, the compressed air is released and burnt together with natural gas in a combustion chamber. A turbine is driven by this expandable complex combustion gas, which in turn drives a generator to produce electricity [54], [57].

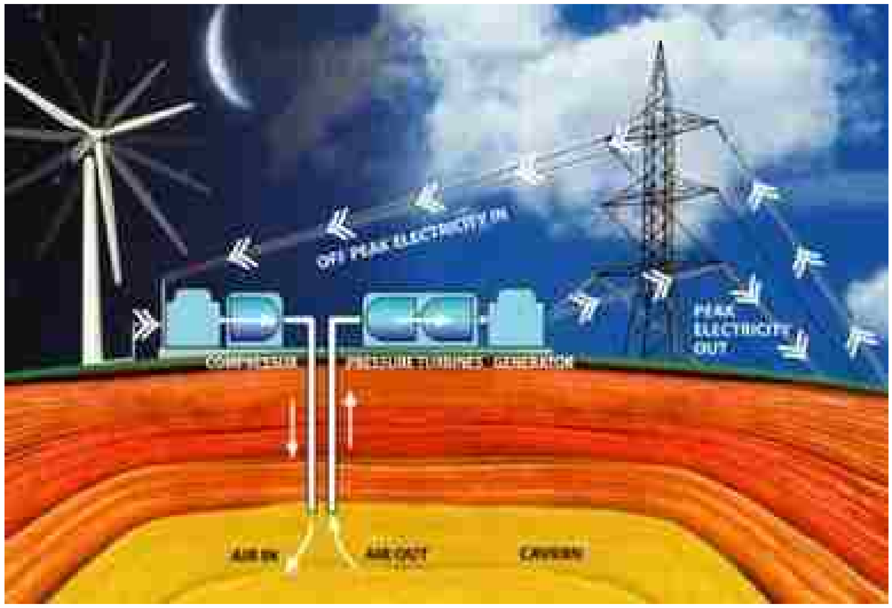

Figure 9 Configuration of CAES [60]

A typical CAES plant consists of four main parts, viz. a compressor, a cavern for the storage, a motor generator and a gas turbine (Figure 9 above). Although it has some geological constraints, the CAES generates more power than the conventional gas-fired plant. In fact, [57] it can generate three times more power.

3.2.2 Electrical ESS

3.2.2.1 Conventional Capacitors, Caps

Conventional capacitors' principle of operation is relatively simple. They store energy by the removal of charge carriers which are mainly electrons from one electrode and deposit them onto the other electrode plate. This process builds up charges of opposite sign on both sides. Therefore, a huge potential difference is created between the two plates, which can be harnessed in an external circuit [54]. The main advantage of the conventional capacitor is its high power density and its instant charging/discharging events, but has low energy density. Figure 10 shows an illustration of the conventional capacitor. Hence, the associated equations are:

$$C = \frac{\varepsilon . A}{d} \qquad 3.2$$

and

$$E = \frac{CV^2}{2} = \frac{\varepsilon . A}{2d} . CV^2 \qquad 3.3$$

Where

C = Capacitance in Farads, F; d = distance between the plates, m

A = Surface of the plates, m^2

V = Potential difference created by the charges, V

E = harnessed energy, J

All these parameters are shown on the Figure 10.

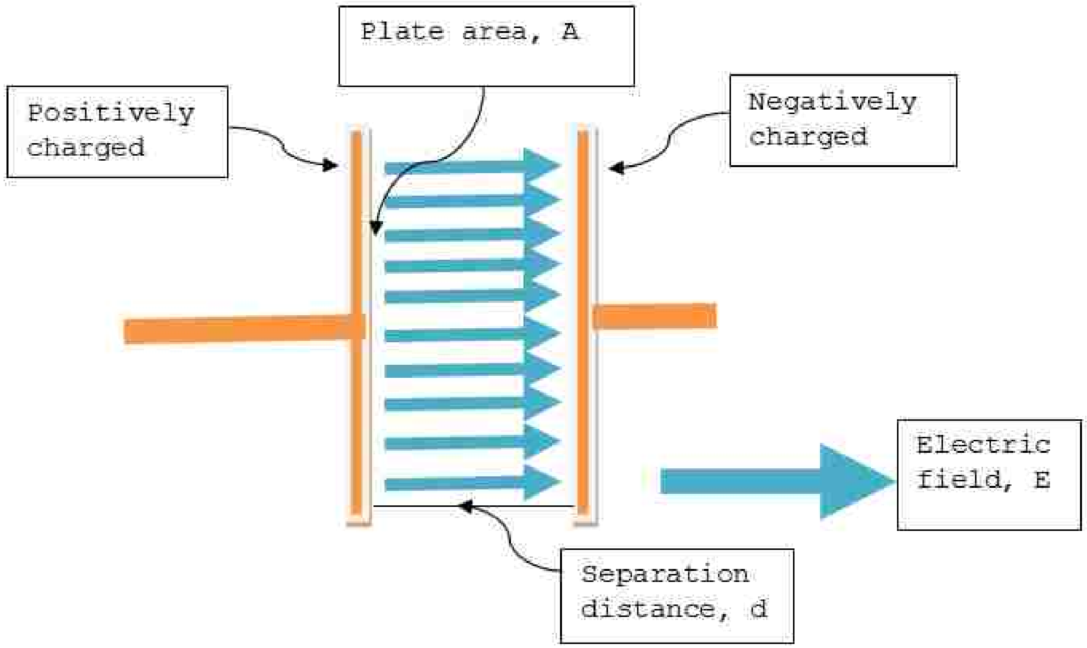

Figure 10 Schematic diagram of a conventional Cap

3.2.2.2 Ultra-capacitors (UC)

Most of the electronic and electric devices such as HEV, cell phones, laptops, etc.. require the use of battery. Since the 19th century when it was first discovered, not much has been done in order to improve it. Therefore, an alternative to it is the UC, which could allow an instant charge in about a minute with thousands of charge and discharge cycles [27]. However, despite the great advantages of supercaps such as long life span (100,000cycles at 80% depth of charge), low maintenance cost and the higher efficiency (95 to 98%), it would never be suitable for bulk energy storage applications due to its inability to provide power for more than a minute [47]. Infact, different terminologies could be used interchangeably and are all used to designate the same thing. Those terminologies are: ultracapacitors, supercapacitors, electrochemical capacitors, double-layer capacitors and electrochemical double-layer capacitors.

3.2.2.2.1 Chemistry of UC

Capacitors are physical devices used to store electric charge with any chemical reaction. UC work in a similar way to traditional capacitors, but they differ slightly in the sense that they are not separated with insulators or dielectric. The reason is that, due to polarization of molecules in the material, the dielectric creates a huge capacitance for regular capacitors (Figure 11 below). Rather, they use virtual plates of the same substrate. The anode and cathode are made up of carbon immersed in an aqueous or non-aqueous electrolyte which could be organic based. With high surface area, the electrodes become positively and negatively charged and complete the cell. At the electrode/electrolyte interface, the principle at work is the double layer capacitance. As opposed to the conventional capacitors, UC make use of its electrodes to create electrical charges by chemical reactions. Charges accumulate on both carbon electrode surfaces and the ions of opposite sign, by the law of electrostatic physics arrange themselves on the electrolyte side (Figure 12). The separator acts like the regular dielectric and prevents the charges from moving between the electrodes [29]. Therefore, knowing the potential difference between the plates and the electric charge, the capacitance can be calculated as follows:

$$C = \frac{Q}{\Delta V} \qquad 3.4$$

Where:

C is in Farads

Q in Coulombs and

V in Volts

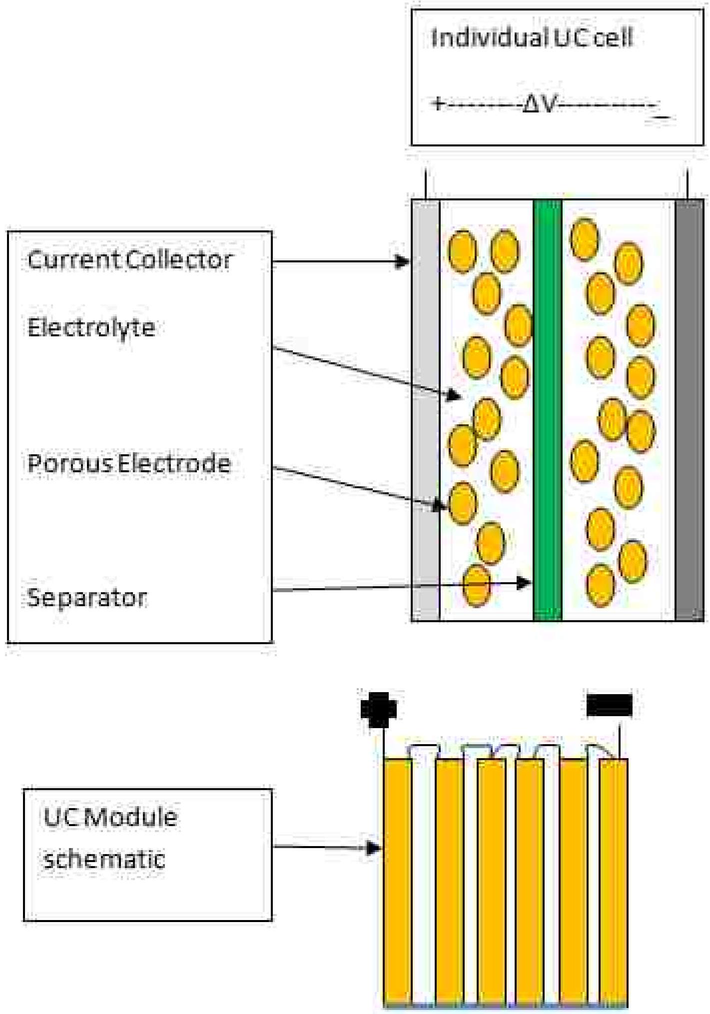

Figure 11 UC cell

Quite often, capacitance is determine as a function of the area of the electrode plates, the distance between them and the dielectric constant, ε, of the medium. Hence, the capacitance is determined as follows:

$$C = \frac{A\varepsilon}{4d} \qquad 3.5$$

Hence, making the electrode surface area large enough and shortening the distance between them can allow UC capacitance of up to thousands times greater than that of ordinary dielectric capacitors.

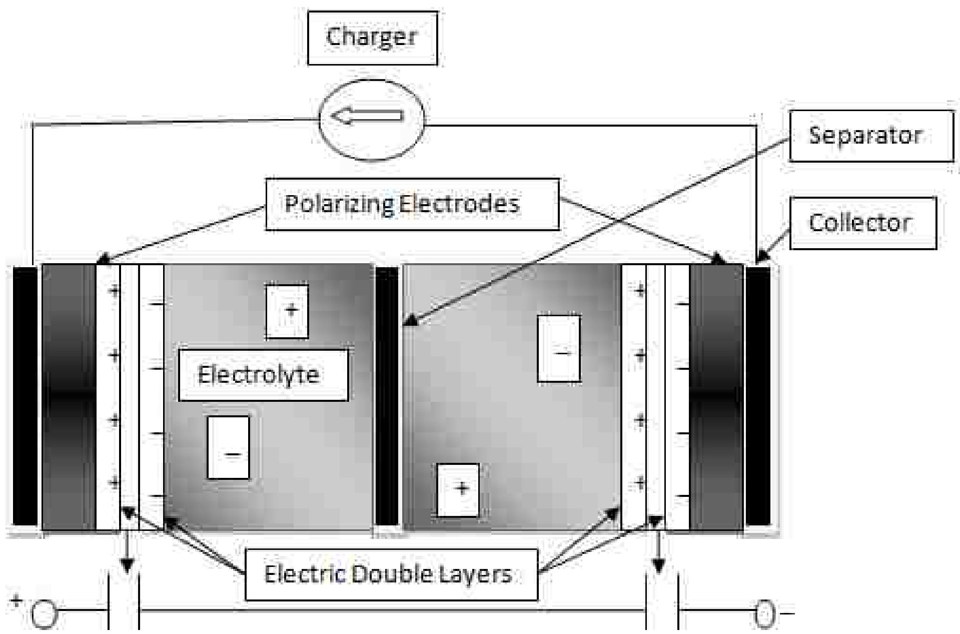

Figure 12 Configuration of UC

The energy of the capacitor can also be determined with the knowledge of the capacitance and the voltages. It is directly proportional to the former, but inversely proportional to the square of the latter as shown in the equation below [31]:

$$E = 0.5C(Vi^2 - Vf^2) \qquad 3.6$$

A little knowledge of mathematics shows clearly that the energy is improved greatly by increasing the voltage instead of the capacitance.

3.2.2.2.2 Properties of UC

The most important advantage UCs have over batteries is their ability to charge and discharge without degrading. Batteries are used in our daily life for variety of applications. An example is that our cell phones can be kept on for two days with only one 1800 mAh Lib. Hence, they are characterized by a low power density that one would never expect to recharge it in few minutes. In other words, recharging it will take longer time. On the other hand, with the conventional capacitors, that could be easily achieved as the charging and discharging is as fast as 30 ms though they can’t store enough energy in that short time. It can be seen from Figure 13 that UC are the perfect bridge between regular capacitors and batteries because they have lower power density, but they have high energy density. Therefore, neither the batteries, nor the conventional capacitors have those two characteristics [28].

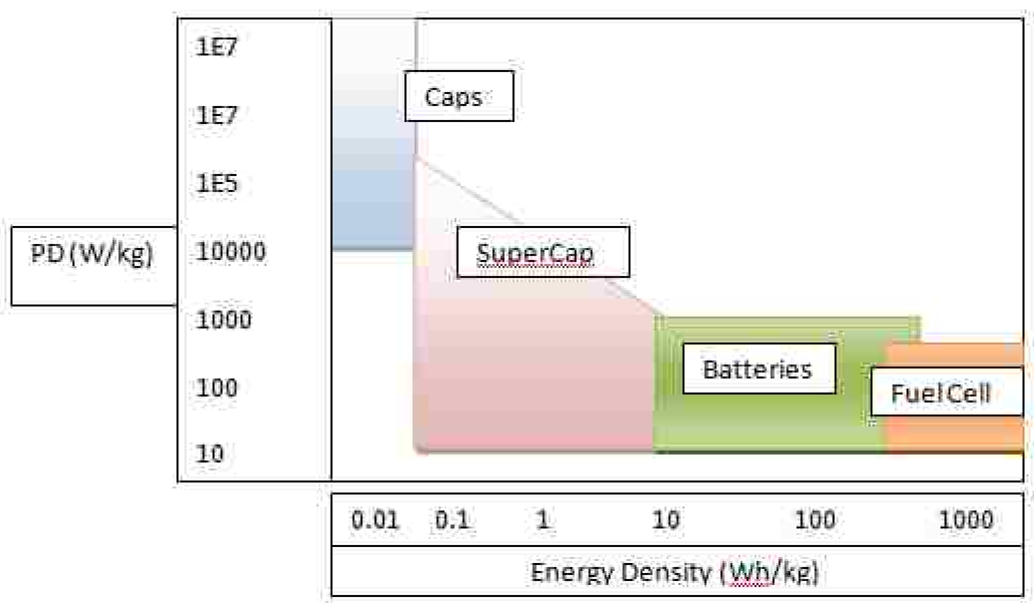

Figure 13 UC power versus energy graph

3.2.2.2.3 Some areas of UC applications

Their quick bursts of energy make them very desirable in PV applications especially to cover transients due to cloud passing by. In a study similar to the one in this thesis, an ultracapacitor is considered in [33]. It is found that the usage of UC for solar power applications could be one of the best candidates for the solutions proposed in here. Hence, it can definitely be one of the future energy storage means for grid-tied PV. Currently, however, it can only be used primarily to store energy during the day and release it later when needed. Although they are more expensive than batteries per energy unit, UC are suitable for a wide range of applications [32]. The advantages of UC are tremendous and countless. They are clean, maintenance-free, environmentally friendly, etc.

On the other hand, they are widely used in the following applications, viz. UPS/power quality, automotive, trains, buses, aerospace, robotics, telecoms, and elevators, to mention but a few.

3.2.3 Chemical ESS Relevant to EV

Batteries are technically composed of several metallic cells immersed in an ionic solution called electrolyte where-in the chemical energy is converted to electrical energy and vice-versa (charging or discharging) [17]. The more suitable batteries for power applications will be discussed briefly here. The nominal power and energy capacities are labeled on each battery although sometimes those values are interrelated and fixed during the design process [17]. Batteries are most of the time broadly identified by some of their characteristics (details are given in section 3.2.3.1):

- Efficiency
- Lifespan
- Operating temperature
- DOD
- Self-discharge and
- Energy density

Furthermore, in this thesis, emphasis will be put on EV batteries since the intent is couple the used ones with the CPV units to fundamentally offset the electrical power transients on one hand and on another to shave the peak electrical load with cheap electricity.

3.2.3.1 Battery systems

An inadequate and inappropriate battery choice will have a great impact on the entire system performance and reliability especially when the selection is solely based on the lowest cost. As stated earlier, the most commonly used electrochemical energy storage devices are batteries in PV applications. Moreover, they are definitely and fundamentally different from those in motive power applications. Among the most commonly energy storage system for PV applications, lead-acid batteries (LABs) are the most popular followed by an emerging one, the nickel-cadmium (Ni-Cad). Convincingly, Ni-Cad has demonstrated some important features regarding performance characteristics and life-cycle cost [26]. Finally, lithium ion (Li-ion) batteries will also be considered as a third option in this thesis.

3.2.3.1.1 Lead-acid battery (LAB)

Mainly, in this thesis, emphasis will be given to battery energy storage systems based on their chemical and physical properties touching upon their advantages and some of the disadvantages that they do present. The best batteries will be proposed based on their size versus cost ratio.

In this section, special attention will be given to lead-acid batteries (LAB) due to their cost-effectiveness. Succinctly, their chemistry and some of their valuable properties are presented in this thesis. By presenting a critical analysis in here, engineers who are already working in the field of renewable and those who are yet to join this flourishing branch of the applied sciences will surely find no difficulties in making an educated guess in selecting an energy storage medium. Compared to other alternatives on the market, the cost benefits of the LAB far out-weight that of the former. According to 0, LAB will definitely lead and will be favored above all other systems of energy storage for the next decade until they become less expensive per Joule of energy stored.

3.2.3.1.1.1 Chemistry of the Lead-Acid battery

Basically, the chemistry of LAB is a reversible process depending on whether it is being charged or discharged. The basics of LAB cell operation are shown in Figure 14 below. The electrolyte is a sulfuric acid solution in which a lead cathode and a lead oxide (PbO_2) are immersed. As clearly stated in 0, Figure 14 below shows the discharging process that takes place at the anode. It consists mainly of an exchange of oxygen cations from the anode with sulfate anions of the solution. This same process of discharging evolves differently at the cathode. Hence, the sulfate ions from the solution (electrolyte) react with the lead cations to form the lead sulfate ($PbSO_4$). The acidity of the electrolyte is based on the number of sulfate ions present. In other words, the higher the number of sulfate ions, the greater the concentration of the acid. This whole process means that power is being delivered to an external load and the equivalent equations are as follows:

$$PbO_2 + 4H^+ + SO_4^{2-} + 2e- \rightarrow PbSO_4 + 2H_2O \qquad 3.7$$

And

$$Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e- \qquad 3.8$$

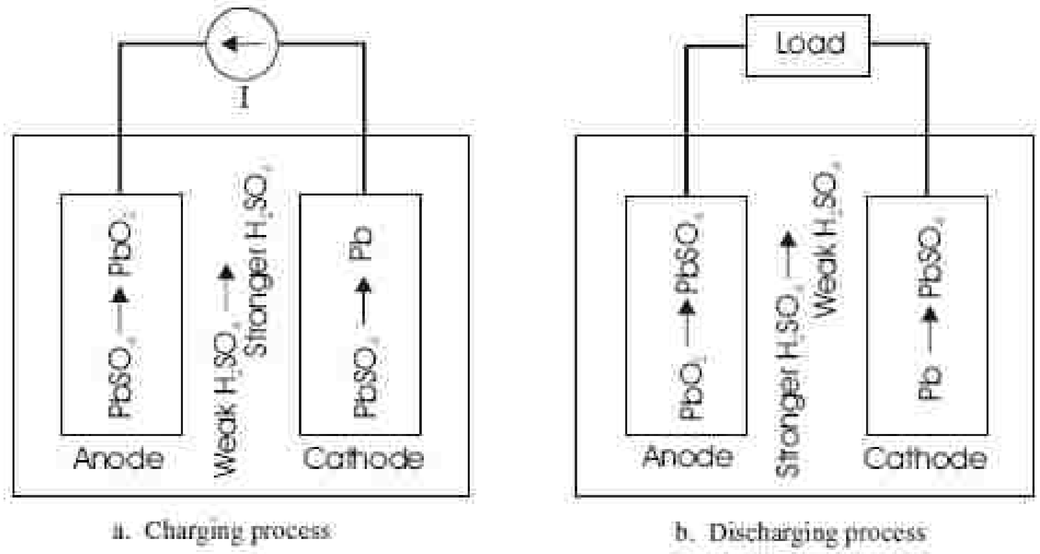

Figure 14 Basic operation of lead-acid battery

On the other hand, during the charging, the whole process is reversed because the external voltage is greater than the internal one, resulting in a flow of current into the battery rather than out of it. In this case, the battery is said to be charging 0. The reversible equivalent equations are as follows:

$$PbSO_4 + 2H_2O \rightarrow PbO_2 + 4H^+ + SO_4^{2-} + 2e- \qquad 3.9$$

And

$$PbSO_4 + 2e- \rightarrow Pb + SO_4^{2-} \qquad 3.10$$

LAB has a potential difference of 2.12 V 0 between the electrodes provided that the cell is fully charged. These cells can then be connected in series to achieve the desired voltages, viz. 6V or 12 V, which are the nominal voltages of a typical LAB. Externally, batteries of the same nominal voltages can be connected either in series and/or in parallel in order not only to attain the desired voltage combination, but also the current necessary for a specific application.

3.2.3.1.1.2 Properties of a LAB

As stated earlier, the process of charging/discharging is ideally reversible, but in practice it is not as it should be because the rates of charging/discharging and the temperature of operation all dramatically affect the performance of the battery. Hence, it is generally known that the word acid means the presence of hydrogen ions (H^+) in a particular solution. As a matter of fact, a loss in these ions represents an equivalent loss in energy. Typically, the charging operation is roughly 95% efficient 0. The same principle applies to the discharging process and the result is, only a maximum of 95% of the energy stored can be restored back due to the internal resistance of the battery. In a nutshell, the LAB has an overall efficiency of 90%.

The Joule effect plays an important role in the charging/discharging phenomena due to the proportionality between the I^2 and the energy lost in the internal resistance. In other words, the higher the current pumped in or out of the battery, the higher the losses and the lesser the overall efficiency 0. So two things happen here: one is a warmer battery has the potential of holding more charge and the second is its lifespan is shrunk if it is too warm for a very long period of time. This is why a charge controller is recommended to monitor automatically the charging/discharging process.

The equation for the discharge rate is: C/x; where C is the battery's capacity and x is the number of hours. Figure 15 below shows different types of discharging rates' effect on a relative amount of charge obtained of a LAB.

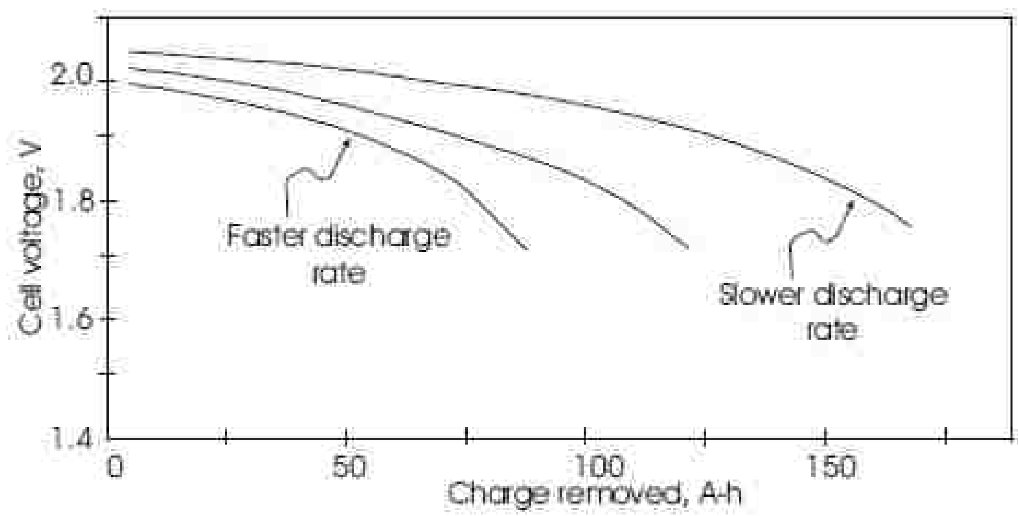

Figure 15 Different discharge rates

For a better lifespan and efficiency, a typical LAB should not be discharge to less than 75 % of their capacity 0.

To overcome this particular problem, in deep-discharge LAB, antimony (Sb) 0 is being used to strengthen the lead. Batteries of this type can be cycled down to 20% of their initial capacity. These types of batteries are used in many applications such as marine, golf carts as well as in PV systems. The life expectancy of a deep-discharging battery is highly dependent upon its depth of discharge although they were designed for that purpose. By virtue of that, in this study, more focus will be given to the use of many batteries operating at shallower discharge rates than lesser batteries which would undergo deeper discharge rates. The latter means that the overall life cycle of the combination of batteries is shortened although its initial cost is lower in comparison to the former. Therefore, it is worthy of note that this is a tremendous trade-off investors should be looking for.

The lifespan of a LAB depends solely on the following aspects [15]:

- How it is being used
- How it is being maintained
- Its charge/discharge rates
- Temperature and
- Other factors

3.2.3.1.1.3 Types of LAB

It is very crucial to note that almost all the batteries customarily used in deep-cycle applications are LAB and they are categorized [15] as follows:

- Flooded or Wet
- Gelled
    - ✓ Sealed
    - ✓ Valve regulated
- AGM or Dry

Due to the fast growing breakthrough in the lithium technologies, one day it may become a cost-effective and competitive energy storage system, which likewise deserves a thorough understanding.

3.2.3.1.2 Lithium battery (Lib)

3.2.3.1.2.1 Chemistry of Lib

The chemistry of Lib involves the insertion of a compound of lithium. The negative electrode (anode) is made up of graphite while the positive electrode (cathode) is in lithium. Its cells have a stable electrode structure i.e. during the process of charging and discharging, Li ions are exchanged between the electrodes immersed in the electrolyte. In comparison to the LAB previously discussed, the output voltage is up to 4.2V [20].

Besides Li, various other active materials may be used in conjunction with it at the positive electrode such as Lithium Nickel Oxide, Lithium Cobalt Oxide, to mention but few.

3.2.3.1.2.2 Properties of Lib

Lib is one of the most promising energy storage devices to look at regarding the high penetration of PV to the grid. Lib has some remarkable properties. Its energy density is as high as 120 W-h/kg [19], and it has demonstrated a positive impact on the environment with respect to emissions and recyclability. It has nearly 100% Faradic efficiency and a cycle life of more than 20 years under ambient temperature [20]. Also extremely important are that it has an efficiency of 95% [19] with a very low self-discharge (<5% per year) [20].

3.2.3.1.2.3 Some areas of Lib applications

Lib are disposable storage units and widely used in many commercial and scientific applications. Due to their high energy density over other storage systems, they have received considerable privilege in applications ranging from electric and hybrid vehicles to telecoms and satellites as can be seen in Figure 16.

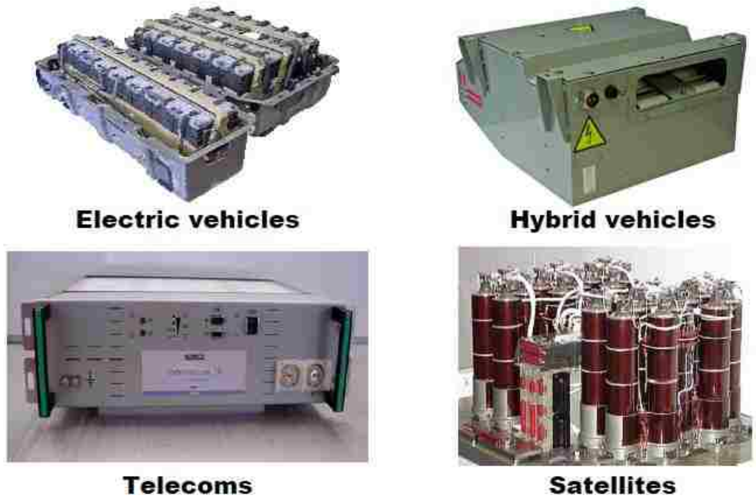

Figure 16 Different applications of Lib [20]

3.2.3.1.3 Nickel Cadmium Batteries- Ni-Cd

3.2.3.1.3.1 Chemistry of Ni-Cd

Similar to the LAB previously discussed, the Ni-Cd is made up of a nickel hydroxide anode and a cadmium cathode plates immersed in a potassium hydroxide electrolyte (KOH). The equivalent discharge equation at both electrodes is as follows:

$$2NiOOH + 2H_2O + Cd \rightarrow 2Ni(OH)_2 + Cd(OH)_2 \qquad 3.11$$

This equation is reversible whether it is being charged or discharged. The fully cell voltage is a little bit lower than that of LAB and is found 0 to be 1.29V per cell.

3.2.3.1.3.2 Properties of Ni-Cd

Ni-Cd has many advantages over LAB 0 from their physical to chemical points of view. They can withstand high temperature and low temperature as well as deep-discharging and overcharging. Based on that fact, one can save up to couple of hundred dollars by eliminating the charge controller. Ni-Cd can be categorized based on the thickness of their electrodes as high, medium and low discharging rates. They can also further be categorized as vented and sealed, although the latter are smaller in size. Their internal resistance is very low compared to that of LAB and that lessens the I^2R losses (Heat). Nevertheless, when they are unused, they lose their charge proportionally to the ambient temperature and their size. At -20^{0}C, the energy loss is nearly zero 0.

The lifespan of a Ni-Cd is highly dependent on the following factors:

- How it is being used
- DOD (less dependent) and
- Temperature

One great advantage of it is that a Ni-Cd battery can last twice as long as LAB. Hence, the fact that they can accept any type of charging mode makes them suitable for PV applications 0. The efficiency of Ni-Cd is about 85%.

The downsides of Ni-Cd are:

- Cadmium is a toxic matter
- Quite expensive
- Cannot be fully charged if they are not fully discharged.

3.3 Battery sizing

The sizing of a battery bank is a delicate matter that has to be carried out with care as both load shifting and transient support require relatively expensive battery energy storage. As a matter of fact, the perfect sizing of the battery capacity is vital in order to meet those goals via the avoidance of an under-sized or over-sized battery (details are in reference [42]).

Many factors need to be considered in the process of sizing a battery. The most important and crucial ones among those factors will be listed here, such as the anticipated daily kWh of energy consumption and the number of hours or days of autonomy of storage needed [1].

These two parameters will be covered in here and an additional size versus cost analysis will also be treated thoroughly in chapter six.

As for the type of battery to use (though in this thesis three major types are studied), an inexpensive option can be applied to accomplish the short-term storage need. Basically three types of batteries are considered in this study due to the fact that their advantages outweigh by far their disadvantages and also they turn out to be the most promising energy storage devices. Additionally, they present relatively a low initial cost, higher lifespan although they may require frequent maintenance.

One thing is, independently of the type of battery to be used with the PV system to be analyzed, i.e. CPV 7700, the larger the battery, the more effective it is in offering the net positive aspects sought. But as a matter of fact, it will become more expensive. Hence, due to the rapid growth in the electric automobile industry, advantage of that will be taken in order to minimize the high initial cost of the batteries. This is to say that since the electric automobiles slowly lose some of their maximum power potential over time, the cars need to have their batteries replaced with new units at some point. However, the batteries that have been removed still have between 5 to 15 years of valuable lifespan left at reduced maximum power level. So, in this thesis, it is proposed that they be inexpensively purchased and added as an option to favor a high penetration to the grid of each Amonix unit. Therefore by doing that, the short-term transient phenomena will be solved as well as load power availability will be increased.

Hypothetically, there are two scenarios to look at herein. The first one would be for each Amonix unit of 53kW nominal power rating, at least a 54kW battery with 20 to 30 minutes of discharge time would be needed to smooth out the erratic power curve pattern of the typical cloudy day as shown in Chapter 2 (Figure 6). On the other hand, for the purpose of load shifting sake, a maximum is needed to be accurately determined. Hence, it is well known that most of the power grids experience two peaks. Those peaks occur either at noon or in the evening [18]. The latter is shown in previous studies to last approximately 2 to 3 hours. So for the purpose of the discussion, the Amonix unit with the help of the ESS would be putting onto the grid a constant power that will be determined (results are in Chapter 5).

It will be shown in what follows that the total power produced from 6am to 1pm goes strictly to charging, for this time frame is considered as off-peak in terms of power consumption. In contrast to that, the system would be programmed to start discharging a constant power during the second time frame considered as on-peak. Furthermore, for simplicity purposes in accordance with NV-Energy energy consumption time division schedule, this period is as 1pm to 5pm.

3.3.1 Sizing Scenario

Load (inverter output) is assumed to be P = 38kW based on the actual performance of the Amonix CPV 7700 installed at the solar site, CER-UNLV; the battery discharge time, T is set to be equal to 1/3 of an hour (≈0.34 hr); E=P.T=12.66kWh

Assume 12% of combined loss such Ch/Disch and wiring from inverter to load 0

Inverter efficiency, ŋ = 98% (assumption)

Load on battery = 12.66kWh/0.98/0.88=14.68kWh

Conversion to Ah at the battery voltage (assumed to be 24V)

14.68kWh x 1000/24V = 611.98Ah

The batteries should not deliver more than 80% of their capacity. The factor that accounts for that is 1.25 0. This means that if 20% of their capacity is left, the charge controller will shut them off automatically.

611.98Ah x 1.25=764.98Ah

Therefore, the battery size for smoothening out the power intermittencies is **764.98Ah**.

For simplicity purposes, other factors are neglected in this battery sizing exercise. Furthermore, the energy capacity of the battery bank is to be determined since it will be of great interest in the section reserved for the economic analysis. Hence, knowing the capacity of the battery and after rounding it to an even number, the theoretical energy capacity is:

$$E = Ah * V = 765Ah * 24V = 18360Wh = 18.36kWh \qquad 3.12$$

Having done that, the suitable batteries can now fit in without any problem by connecting them either in series and/or in parallel to achieve the above storage capacity. On the other hand, it’s worth noting that [48] EV batteries are available either in singles or packs of 10 to 52 individuals with a variety of voltage ratings ranging from 6, 8, 12, 24V, to mention but few.

- 4 packs of Li-ion batteries with specifications of 24V, 200Ah would perfectly do the job (See Figure 17 a. below).

- 43 packs of AGM, VRLA lead acid with specifications 24V, 18Ah would also do the job as well (see Figure 17 b. below).

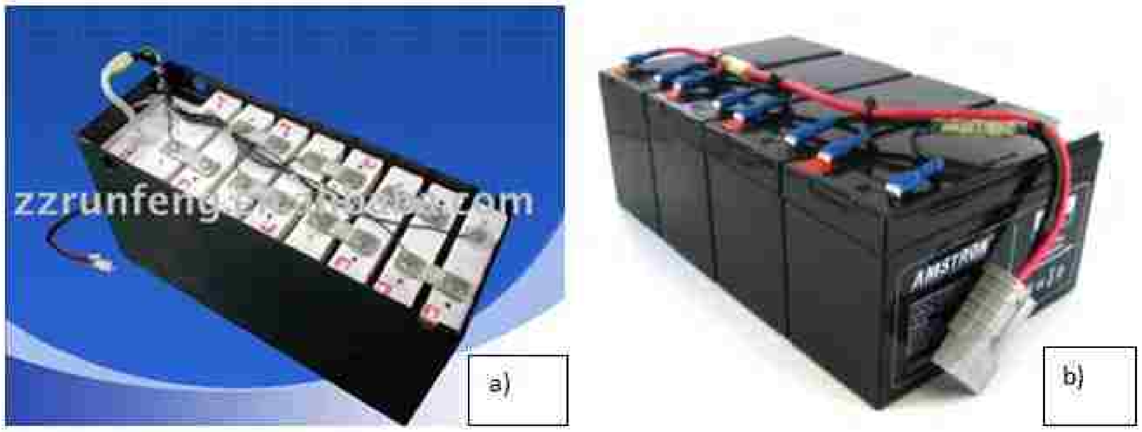

Figure 17 Two types of suitable battery packs a) Li-ion 24V, 200Ah; b) AGM, VRLA 24V, 18Ah [51]

3.4 Comparative evaluation of ESS

Before selecting any type of energy storage device, it is very important to consider few of its most significant parameters such as efficiency and life cycle. Additionally, the total cost of the storage device is heavily dependent on those parameters in a sense that choosing the low efficient ESS has a direct implication of high effective energy cost. Likewise, choosing a lower cycle life ESS will have the same effect of increasing the overall cost since the system definitely needs to be replaced more often [54].

3.4.1 Main features of ESS

As stated earlier, each one of the ESS briefly discussed above has one way or the other a slight flaw that prevents it to meet all the requirements. Putting it in other words, there is no ideal ESS up to date. The ESS is chosen based on one's purpose. Therefore, the ESS that fits the most of the goals will be the best among all. Table **3**, Table **4** and Table **5**below describe, respectively the applications, the characteristics and their current price range.

Table 3 ESS areas of applications [55]

Technology	**Advantages**	**Disadvantages**	**Commercial maturity**	**Applications**
Lead-acid	Low capital cost	Limited cycle life when deeply discharged	High	Power quality Management/ Load leveling
Li-ion	High power/high efficiency	High cost and needs special charging circuit	Medium	Power quality management
NiCad	High power/high efficiency	Low energy density, High Cost	High	Power quality and energy management
UC	Long cycle life/high efficiency	Low energy density	Medium	Power quality management
CAES	High capacity	Special site requirement need gas fuel	High	Energy management
PHS	High capacity, low efficiency	Especial site requirement	High	Energy management

3.4.2 Summary of the technical comparison of some of the ESS

Though they are unanimated things, batteries usually function best at RT like humans. To further the explanation, any bias towards the cold or the hot will automatically disrupt their performance and/or lifespan. Hence, the internal resistance of the battery will be lowered by any operation of it at elevated temperature thus improving its performance significantly. That state of being will speed up its chemical metabolism. Nevertheless, the down side of that fact is, the battery's longevity is shortened provided that it has to operate under such a condition for long periods of time.

A certain amount of energy can surely be taken out of a predetermined storage system only after a certain time period of energy storage has passed. For that to happen, energy efficiency and the associated self-discharge not only have to be combined, but they also have to be expressed in terms of charge retention. On the other hand, when the ESS is indirectly connected to the grid, one of the major factors of value would undeniably be the efficiency of the selected type of EES that would be adding importance to each kWh sold. Moreover, if things go as predicted, according to [61] the cost of the electricity supplied from ESS would increase in the not-so-far future.

Table 4 ESS characteristics [54], [55], [57]

Technology	Lead-acid	Li-ion	NiCad	UC	PHS	CAES
Efficiency (%)	65	80	60-65	95-98	70	73
Cycle life charge/discharge	1000	800 @ 60% 300-500 @ 80%	2500	100,000 @ 80% DOC		
Size range (MW)	0.001-40		1-10			
Operation Temp. (◦C)	-5 to 40	-10 to 60	Ambient			
Energy density (Wh/kg)	50	100-125	50-75			
Self-discharge	0.3% per day	<10%	0.6% per day			
Environmentally friendly	No Issues with processing of lead.	No	No		No	No
Disadvantages	Limited cycle life when deeply discharged	Shorter lifespan whether used or not	Heavy metal Cd recycling issues			

3.4.3 Economical evaluation of some ESS

As opposed to the previous section which was focused solely on the technical aspects of different ESS, this particular section will focus on their cost of investment. Table **5** gives a brief summary of how much the specific ESS of interest would cost based on a previous study [61].

Table 5 Summary of selected ESS price range [56]

Technology	Price Range
Lead-acid	$300–600/kWh
Li-ion	>$600/kWh
NiCad	$1000/kWh
UC	
PHS	
CAES	

CHAPTER 4

4. System Analysis

To investigate the "Buffering PV Output during Cloud Transients with Energy Storage", a certain number of things were done prior to the analysis. The first thing was the data gathering such as the output of the CPV unit, the NV Energy summer load, etc. from the CER at UNLV (Figure **18** below). The following step which was one of the more tedious jobs consisted of a manual verification of the whole data set. One important thing to note here which adds to the complications was the missing data for whole days due probably either to maintenance operations or to a sudden shut down of the data logger. Luckily, though the corresponding DNI continued to be recorded by other means. So, by virtue of that, some manipulations have to be done in order to bridge the gaps. Therefore, whenever the DNI is greater than 50W, there are some calculations to be done in order to fill in the blanks. The equation is as follows:

- If DNI>50W, then the net power, P is approximately given by [62]:

$$P = 0.0455 \times DNI - 0.99 \qquad 4.1$$

Where DNI and P are all in W/m^2

For the proposed study to be done, there are basically two ways to achieve it. The first and most expensive way could be to physically set up the entire system necessary for the present study. It would be comprised of a CPV 7700 unit, battery bank, a control box, the balance of the system, etc. Unfortunately, that is not possible within the scope of this study, but may happen in the future. A second way that was used is to carry out some theoretical CPV grid-tied feasibility simulations based on computer codes developed for this thesis. The programming tool at hand, Matlab, was chosen for its availability, ease of use, and computational efficiency.

Another important aspect of this study is how to come up with the proper size of the battery that would not only mitigate the transients of the output power signal due to the intermittent nature of solar, but also displace a certain amount of less valuable power generated to the off-peak period and move it to the peak time. As a matter of fact, two parameters were found to be really crucial in sizing the battery, viz. the discharge time, T, and the maximum average output power of the unit. Figure 18 below is the CPV 7700 at the CER, where the study was conducted.

Figure 18 CER Solar site, CPV 7700 UNLV

The performance data of the unit which are stored in an Excel format, are then imported into the Matlab codes by using the built in command xls.read. Furthermore, the study is conducted throughout the entire summer season and the results displayed cover the period of 6am to 5pm on a daily basis. So, in order to avoid any discrepancy in the reading since the codes are set up to read a reference (Hour), only full hours starting from 1PM which is the beginning of NV Energy's peak hours, are considered.

4.1 The variables and assumptions

The investigation of the feasibility of high CPV penetration into the grid with a battery buffer to smooth out the generated power wouldn't have been an easy task without the preliminary definition and simplification of the problem. Therefore, for simplicity purpose, the proposed power which will be put onto the grid in order to alleviate the peak burden was first treated as a variable starting from 5kW of power generated with an increment or decrement of 5kW each time the guess was above or below any arbitrary reference point. When a certain amount of power threshold point was reached then the increment of 5kW was manually reduced to 2kW then 1kW for better and precise values. In a like manner, the battery was also treated as a variable parameter until it closely matched the calculated value. The program was then re-run as many times as needed in order to hit the final constant power output.

At this point, the final value corresponded to a certain level of ideal power that the unit can afford based on the predefined characteristics was achieved. Finally, there is one important factor called "system output" which measures the quality as well as the performance of the system. So, say if the plot of system output and that of the base power generation, "BaseGen" matched exactly, the battery bank is perfectly sized and corresponds to the goal set.

On the other hand, in order to theoretically calculate the power and energy capacity of the battery bank and the number of battery modules required, some assumptions were to be made. Hence, not only the power output of the CPV 7700's inverter is assumed to be constant and equal to 38kW but also the discharge time is assumed to be equal to fractions of second to a maximum of 0.34h. Additionally, the combined charge and discharge loss is assumed to be 12% 0; the inverter efficiency is also assumed to be equal to 98%. Finally, the battery nominal voltage is taken to be equal to 24V nominal. All the above assumptions led to an energy capacity of 765Ah or 18.36kWh which was later on fit into the codes in order to generate all the plots for the analysis. The result was that, the battery power capacity was found to be equal to:

$$E = P * t; P = \frac{E}{t} = \frac{18.36kWh}{0.34h} = 54kW \quad 4.2$$

4.2 Total power generated by the CPV 7700

All the simulation based on numerous trial and errors before reaching the reasonable conclusion was based on the summer 2011 Amonix CPV's power output. Below is an illustration (Figure 19) of the unit's power output for the whole summer season.

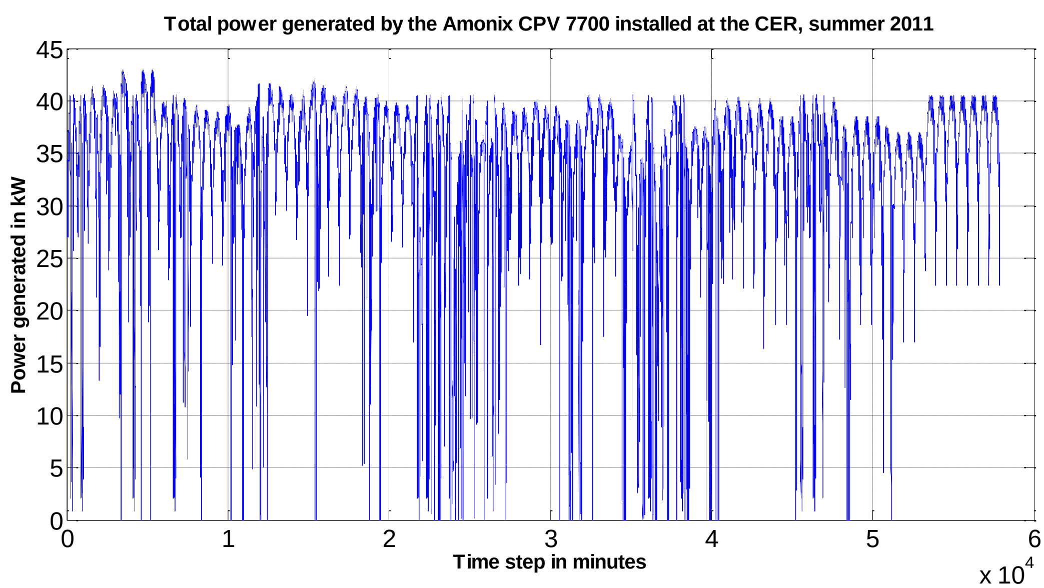

Figure 19 Graph of the CPV 7700 output in kW, CER UNLV

Below (Figure 20) shows a zoom of the generated output power pattern of the first day of the season from the above graph recorded at the CER, UNLV research center.

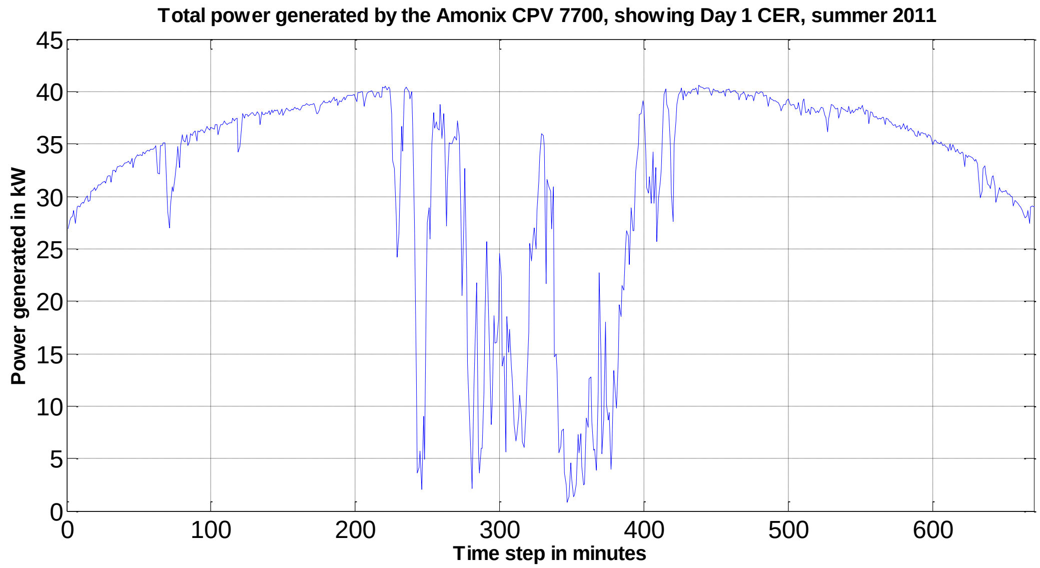

Figure 20 CPV 7700 generated power curve of June 1st, 2011, CER

4.3 How the system functions

The overall operating time of the unit is divided into two parts for the sake of this analysis. The first time frame which is 6AM to 1PM is considered as an integral part of the off-peak time. This specific time frame is neither the focus of this study nor will it be considered the time where the electricity price is higher. Rather, it will be considered as a strategic time whereby the proposed storage system will not only be charged, but will also be storing less expensive electricity to target the peak time. The second, known as on-peak time for this analysis starts at 1PM and ends at 5PM. This latter time frame is very critical in this study and by virtue of that, the system is set up to contribute efficiently in shaving part of the peak load by putting onto the grid constant amount of power.

4.4 Description of the cost analysis

The final part of the investigations carried on throughout this study encompasses the cost-effectiveness analysis of the storage system. For lawmakers to vigorously accept a high penetration of CPV into our energy production midst despite the downside of it, not only must the appropriate buffers be exhibited, but also the economic aspect of it must be convincingly shown. So with that regard in mind, the sole purpose of inserting a whole chapter for the economic analysis is to come up with numbers since they (the numbers) have been known to have a certain power specifically in the eyes of both utility managers and lawmakers. Hence, among the various energy storage systems that could effectively do the job, not all of them are relevant to this study. For that particular reason, all the irrelevant EES are just mentioned briefly and to be able to carry on thoroughly this study, emphasis was put on the rest.

In the scope of this study he used EV batteries are considered which could be purchased cheaply with the provision that they still have several good years to go for their second lifespan. Hence, past literature and the trend on the market have shown that the following battery storage systems will be the most dominant in the EV batteries arena, viz. NiCad, Li-ion and Lead-Acid batteries. The section clearly identifies all the possible alternatives, their associated consequences and their costs. The economic analysis will never be totally accurate for this infant industry, but rather it will be informative and equips the buyer with the decision making tools needed. As a consequence, each battery system is fully scrutinized economically without ignoring what they present in terms of advantages and disadvantages. The final decision is left to the buyer, as stated above to put the best of the tradeoffs forward for purchasing considerations.

CHAPTER 5

5.0 Results and Discussion

To check the feasibility of the CPV 7700 high penetration onto the grid with a proper battery bank as buffer, several simulations were carried out with different hypothetical variables in order to attain the sought objectives of the present study. Hence, the two following sections will present respectively the results and the related analysis in order to make things not only clearer, but hopefully also convincing to readers.

5.1 Results

Simulations were performed using 87 days' data out of the three months of Summer 2011 CPV output. Differents graphs are provided below in order to set up a clear benchmark for the discussion section that follows. The battery capacity as well as the base constant power generated were kept as variables and at each iteration, results were output until the maximum that the system could handle was reached.

5.1.1 Base power of 15kW with a battery capacity of 30kW

We hypothetically started with these two quantities just for the sake of simplicity though some preliminary estimations (trials) were performed prior to this. As a matter of fact, 15kW and 30kW for the base power generation and the battery capacity respectively turned out to be a good place to begin with as shown by Figure 21a), Figure 22b) and Figure 23c). It is worth of note that some of the figures are really hard to decipher. Hence for that particular reason, the plots for the whole summer season are subdivided into three corresponding to the months of May (a), June (b) and July (c) respectively throughout section 5.1. Therefore, the plots of the three months case per case (all together in one to make up the season) are in appendix A for details.

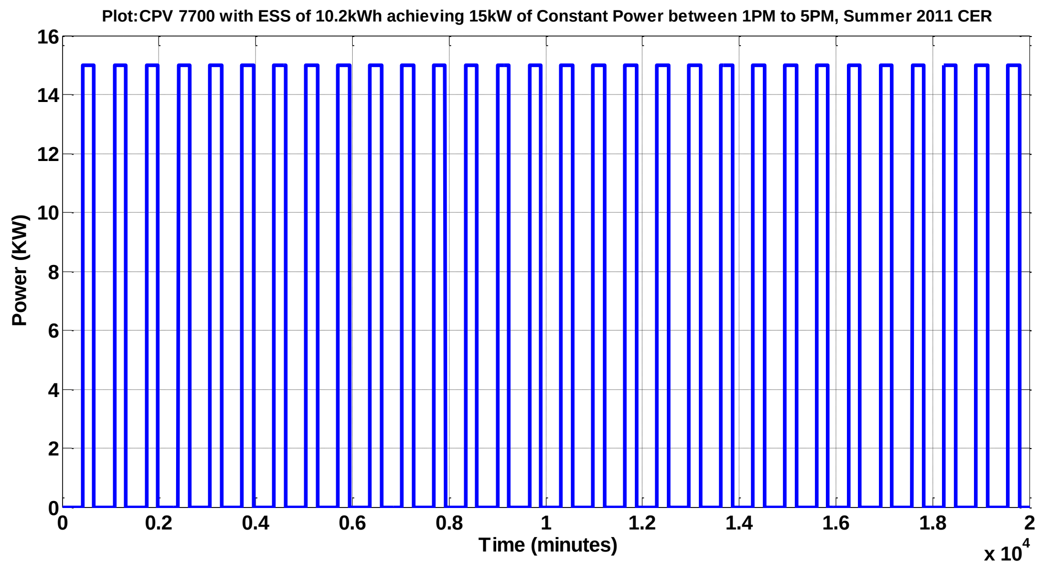

Figure 21 a) Constant 15kW throughout May [1/3 summer] is met with 30kW of buffer

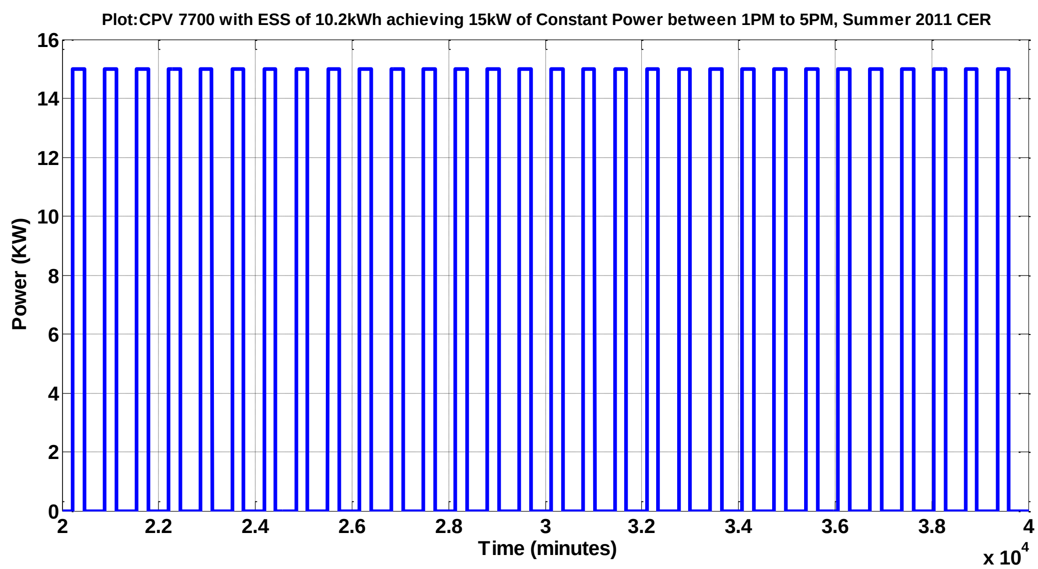

Figure 22 b) Constant 15kW throughout June [1/3 summer] is met with 30kW of buffer

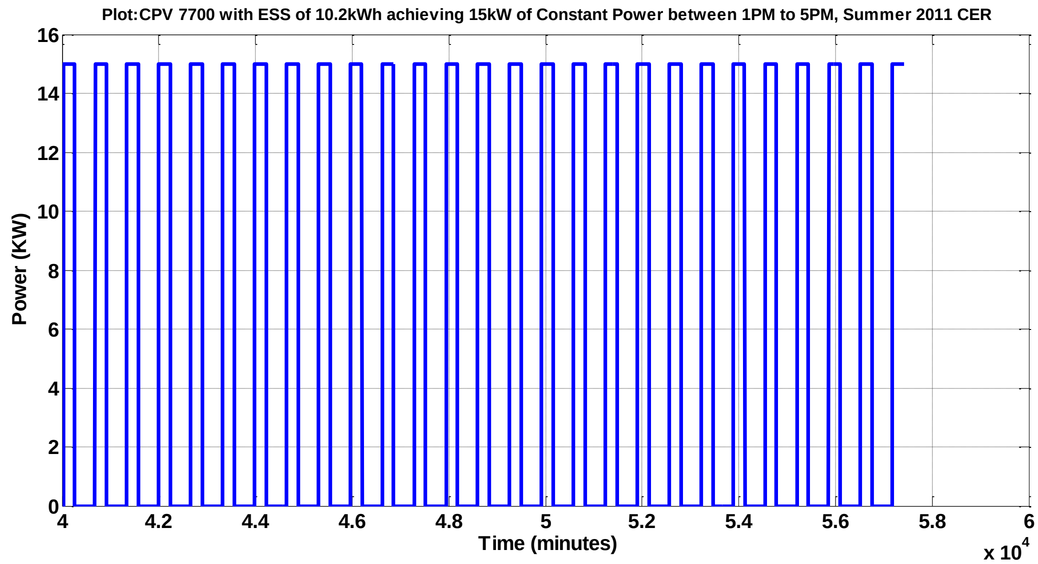

Figure 23 c) Constant 15kW throughout July [1/3 summer] is met with 30kW of buffer

5.1.2 Charge Loss versus Discharge Loss

Figure 24 illustrates all the possible losses associated with the charging and discharging process of the storage unit in the course of its normal operation for the aforementioned capacities. The positive side of the curve in blue is the total loss due to charging and the rest, in green, obviously is considered as those losses due to the discharging process.

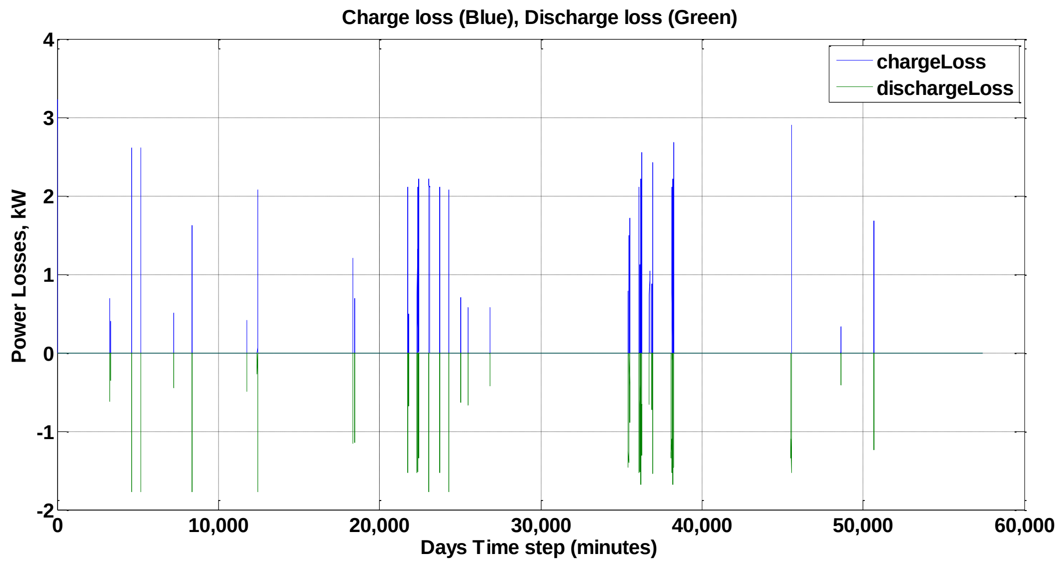

Figure 24 Total charge loss (blue) compared to that of discharge (green)

5.1.3 Charge and Discharge Pulse pattern

Figure 25 depicts the charging and discharging pulse pattern of the whole season with charge being positive ones (+1s) and discharge being negative ones (-1s).

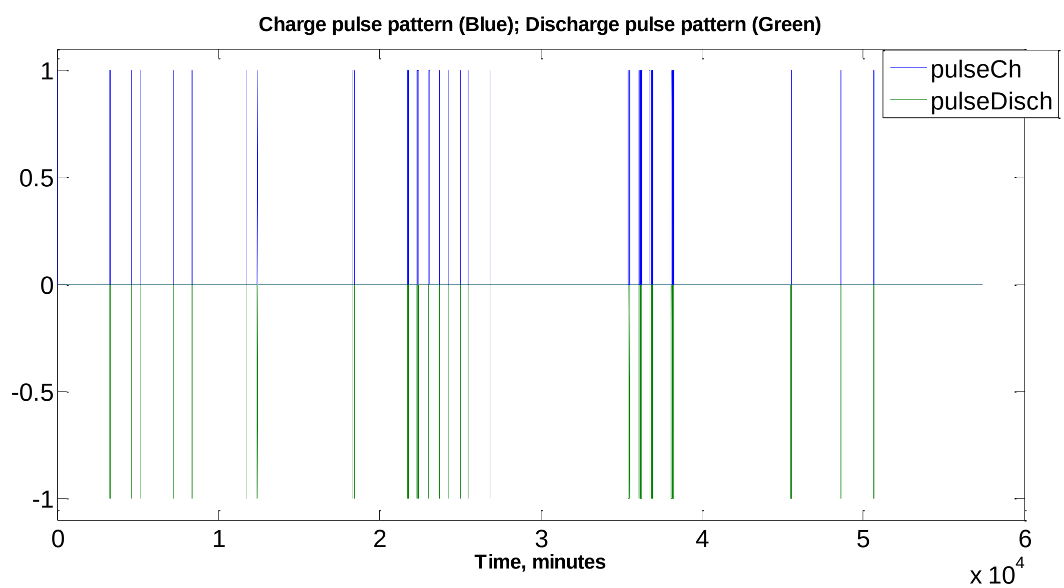

Figure 25 Charge pulse (blue) vs discharge pulse (green)

5.1.4 The maximum power charged (Max Bat Charge=24.58kW)

During the summer season, the battery is constantly either charging or discharging except during night time or when it is fully charged. Some of the exceptions include when it reaches its DOD of 20%. In this latter case the control algorithm will simply disconnect it from the system for safety purposes. Figure 26 illustrates a condensed picture of the battery-charging period and pattern in the course of the season with a maximum of 24.58kW of power occurring in the month of July.

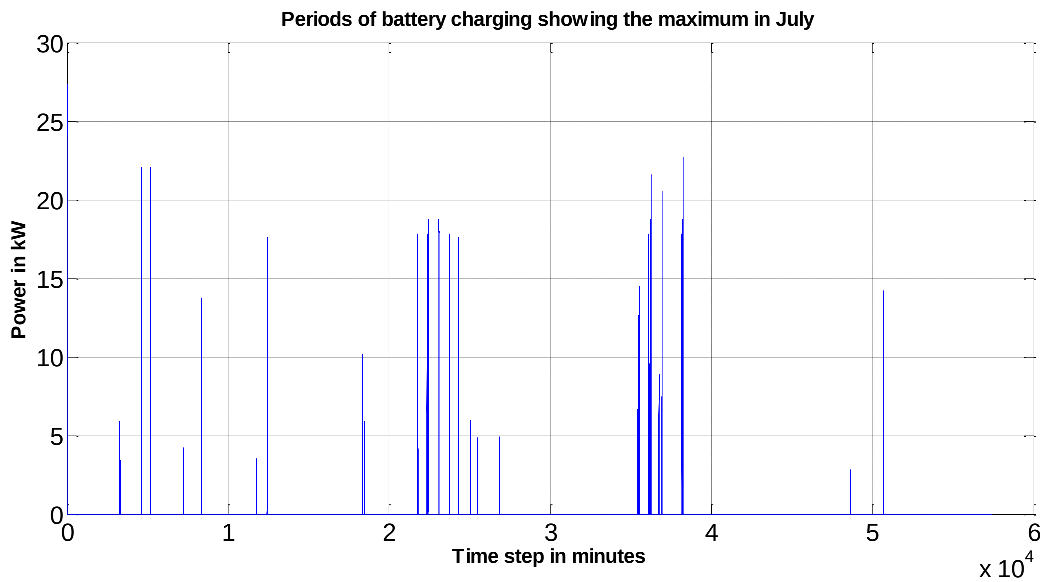

Figure 26 Battery charging periods with a Max of 24.58kW in July

5.1.5 The maximum power discharged (Max Bat Dsch=16.77kW)

In a like manner, the discharging periods and pattern is shown in Figure 27 below with a maximum of abs (-16.77kW). Hence, the negative sign has nothing to do with the power quantity itself. In contrast to charging, the discharging is set up to be negative as it is a custom in power engineering; meaning that it is generating rather than consuming power. Obviously, this also has its peaks, but rather they happen in the first two months as one would have guessed based on the previous knowledge of what occurred in the charging process.

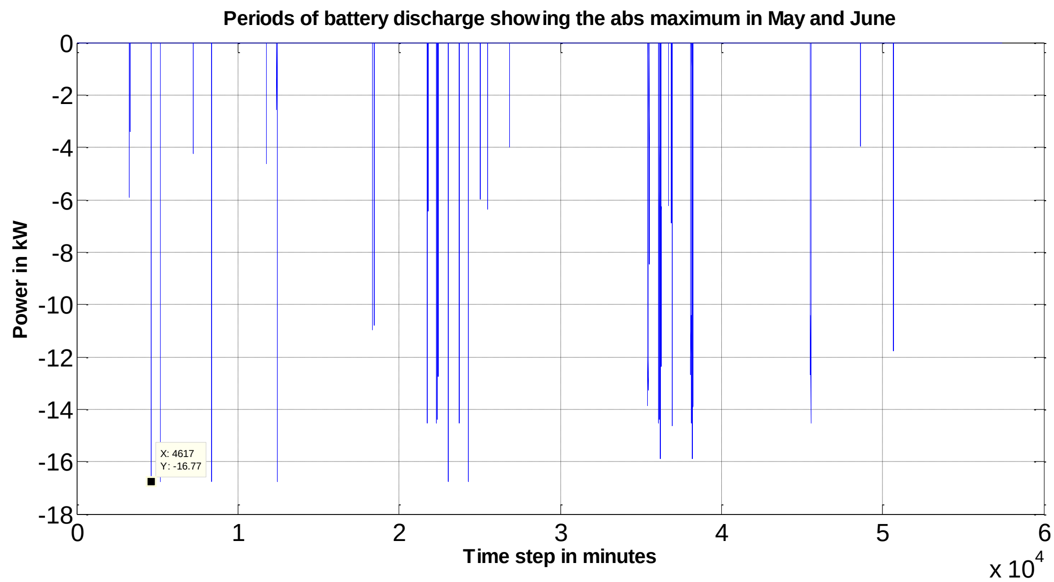

Figure 27 Battery discharge period with a max of 16.77kW

5.1.6 Control strategy adopted (Max= 42.92kW; Min= -15kW)

The whole control strategy adopted throughout this study is based solely on two things. The first thing which is the foundation of all the reasoning is undeniably the output of Amonix CPV 7700 unit and the second being what is chosen to be the base power generated. The latter is actually the "deal" (whatever constant power the system can afford) that the two parties (e.g. producer and the utility company) must agree upon on a daily basis extended to the whole season. So, these two aforementioned concepts were pretty straight forward but nevertheless, they constitute the backbone of our discussion. The base power generated is constantly subtracted from the output of the unit. Here, three scenarios occur. The first one is whenever the mismatch is greater than zero; the excess power goes to charging. The second one is the mismatch may sometimes be equal to zero; in this case, the battery is idle. The third scenario is whenever the mismatch is less or equal to zero, in this situation the battery discharges in order to cap up to the base. Figure 28 below portrays the mismatch with its maxima at 42.92kW and minima at -15kW power.

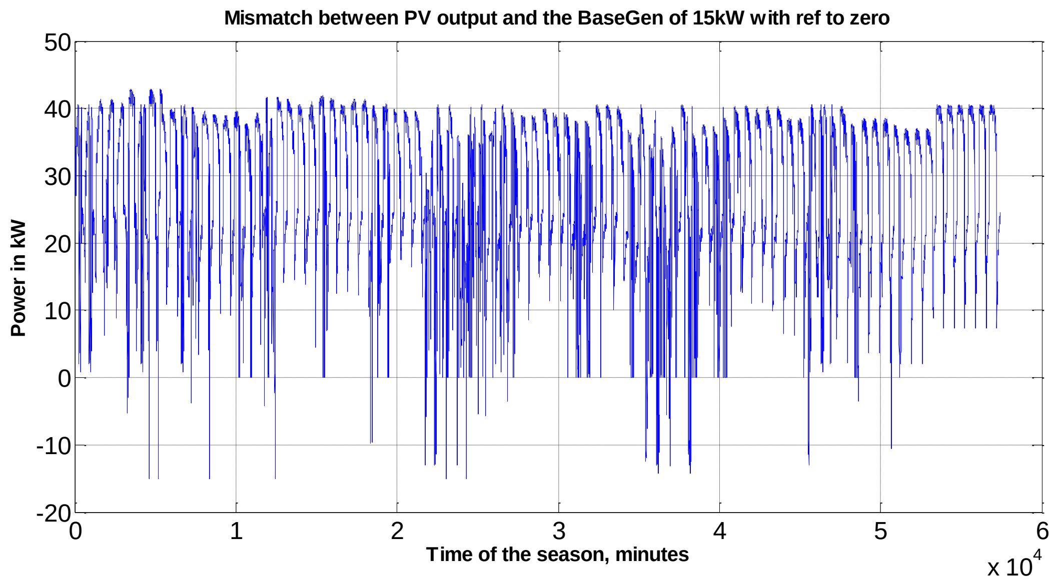

Figure 28 Mismatch power (PV-BaseGen)

5.1.7 Output power of 20kW with 30kW of buffer

The second step was based on the hypothesis of being able to supply the utility with a constant power of 20kW based on the previous battery size. Hence, with this ESS capacity, the project is not viable because there are days that the system cannot meet the contract. Therefore, it is worthwhile pointing out here that there is a crucial implied tradeoff at this stage of the CPV system design. The tradeoff is that the battery capacity has to be higher, meaning higher initial cost than that assumed for a constant power generation to be achieved. Every single run seems to confirm the calculated size of the battery storage system. Figure 29 a), Figure 30 b) and Figure 31 c) depict the plot of 20kW of base generated power of the whole season subdivided into May, June and July for clarity.

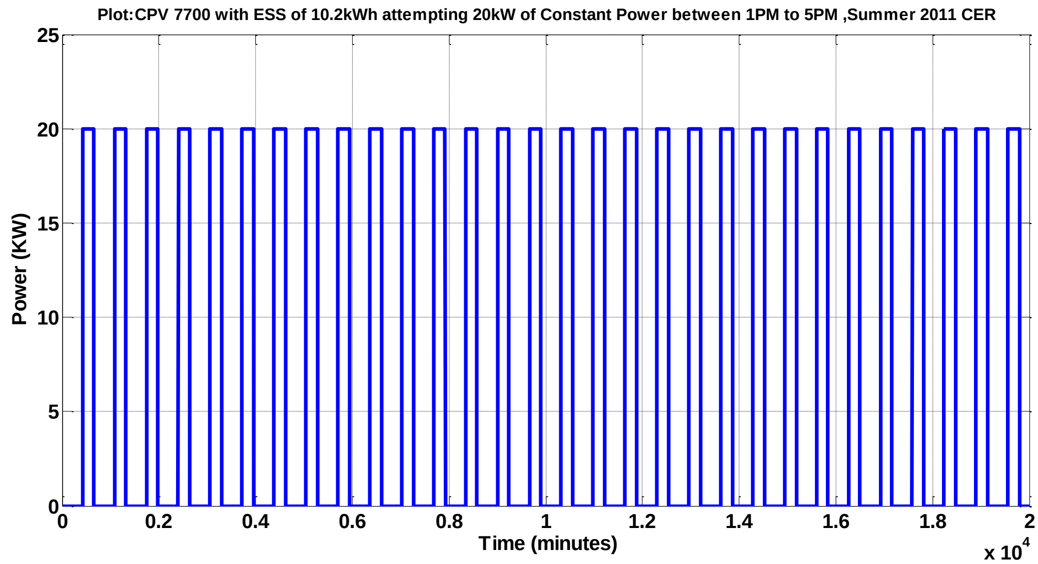

Figure 29 a) BaseGen of 20kW with battery capacity of 30kW, May

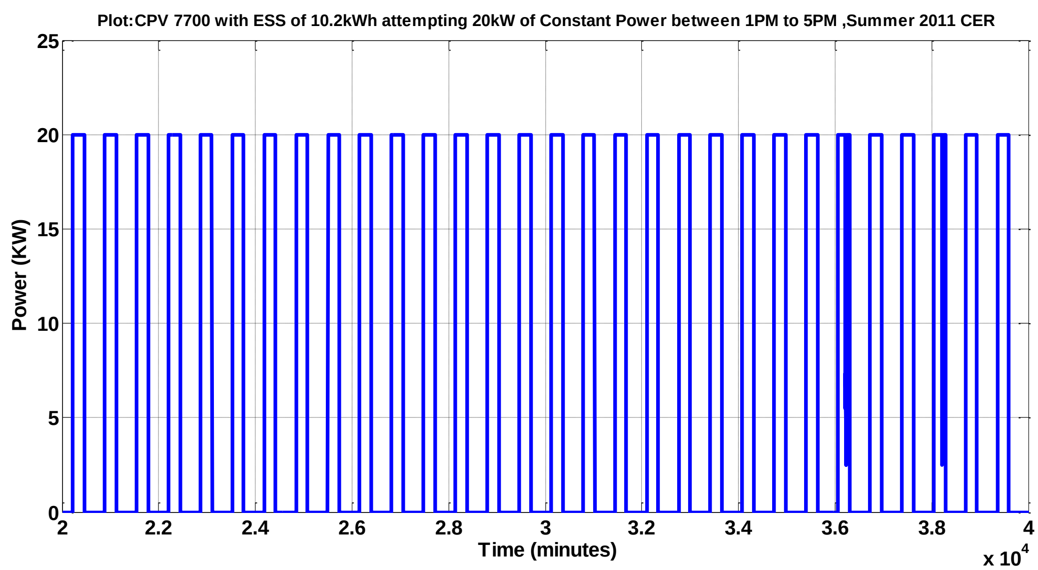

Figure 30 b) BaseGen of 20kW with battery capacity of 30kW, June

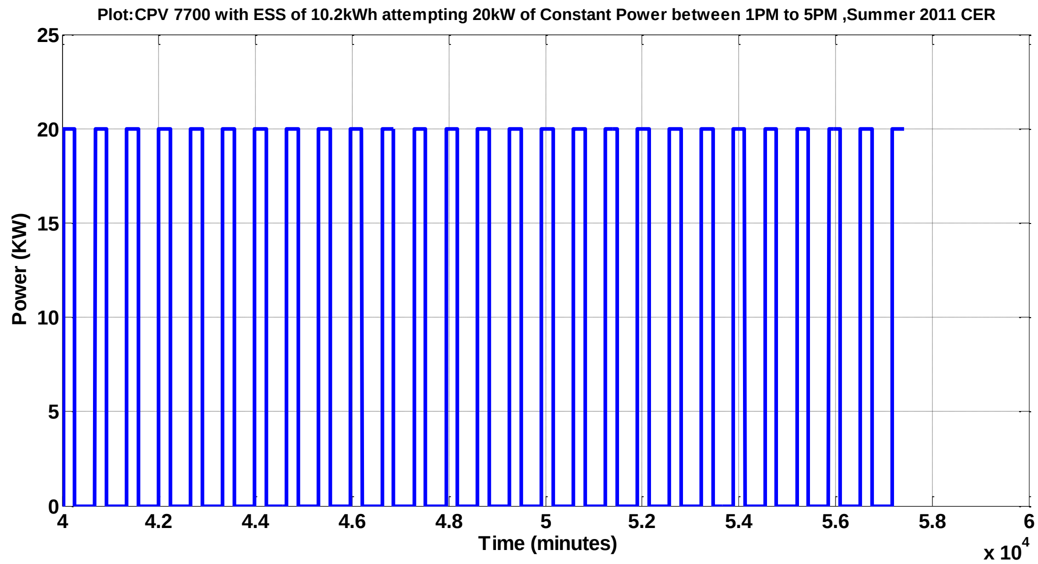

Figure 31 c) BaseGen of 20kW with battery capacity of 30kW, July

5.1.8 Focus on the two days

Taking a close look at Figure 30 b) shows that the two days where the system set up with those configurations was unable to fulfill the terms of the contract. Hence, Figure 32 depicts clearly that somewhere in the afternoon the system (CPV coupled to the battery storage system) cannot meet the demand although the output power is pretty much what is expected almost the entire day.

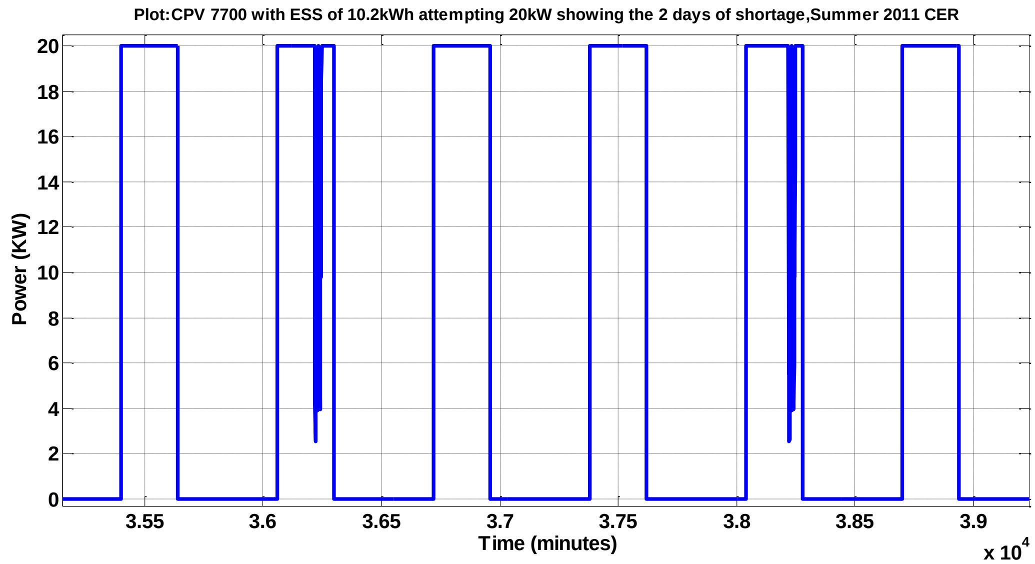

Figure 32 Two days showing P < 20kW

5.1.9 Mismatch pattern based on 20kW constant power

In a like manner as to what happened with the base power generation of 15kW of power, the maximum and minimum mismatches between the two major components considered here are respectively max = 42.92kW and min = -20kW. It is clearly observed that, in both scenarios, the minimum power mismatch level is the opposite of what is arbitrarily set forth to be our base power generated. Figure 33 below shows clearly what is stated here.

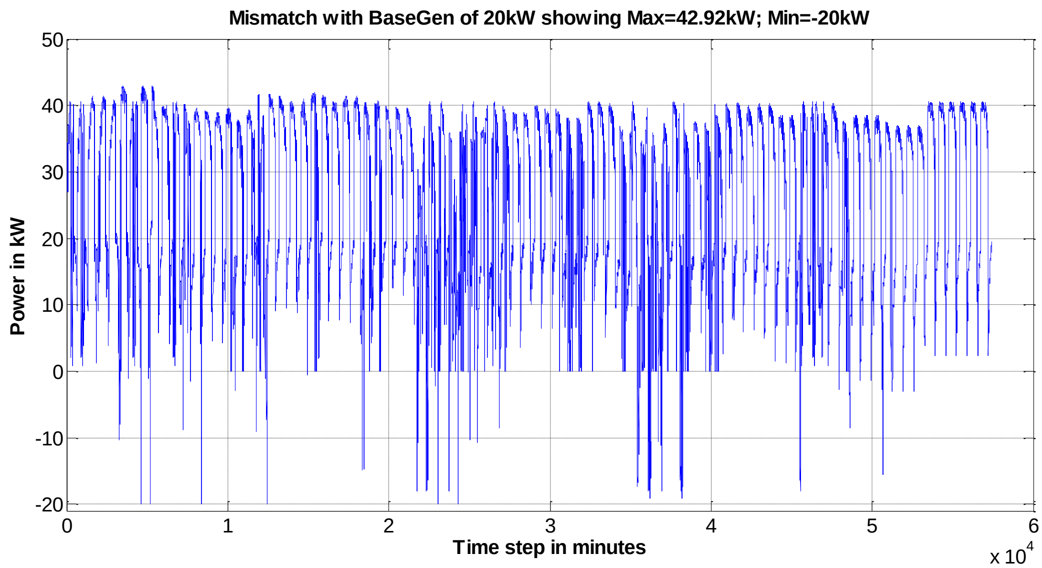

Figure 33 Mismatch pattern, 20kW BaseGen

5.2 Outcome of the sized parameters

5.2.1 Theoretical power and energy capacities

To not only offset any transient in the power generated due clouds on one hand, but also on the other hand to be able to achieve a constant 20kW of power, there is no doubt left regarding the viability of the current project. Hence, the previous assertion has been strengthened by the agreement between the calculated values and the simulation outcomes. As a result, with a battery bank capacity of 54kW with its corresponding energy capacity of 18.36kWh, Figure 34 a), Figure 35 b) and Figure 36 c) illustrate nicely that the sought constant power is achievable without any interruption throughout the season.

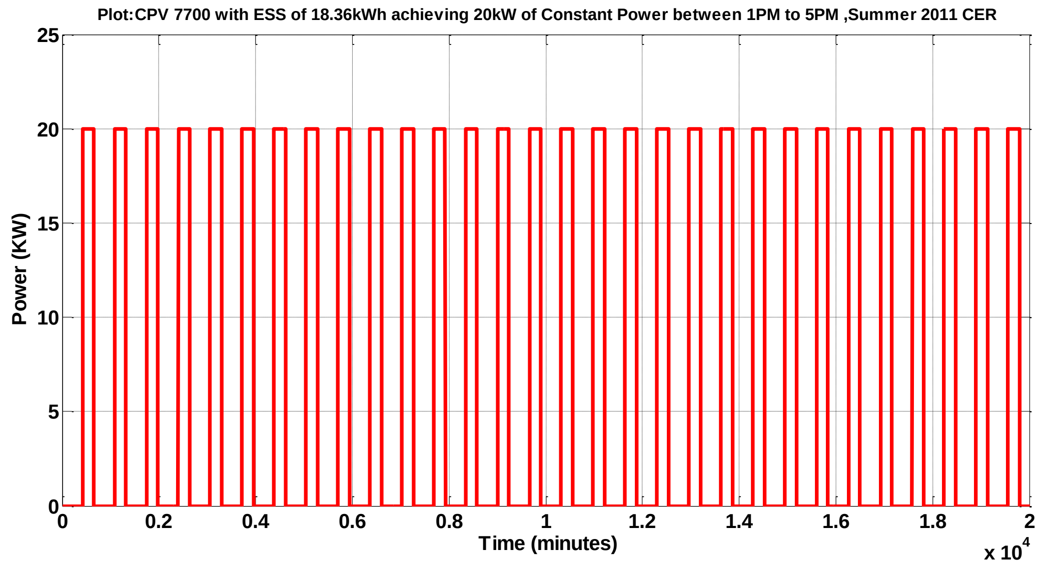

Figure 34 a) Constant 20kW produced based on 18.36kWh ESS, May

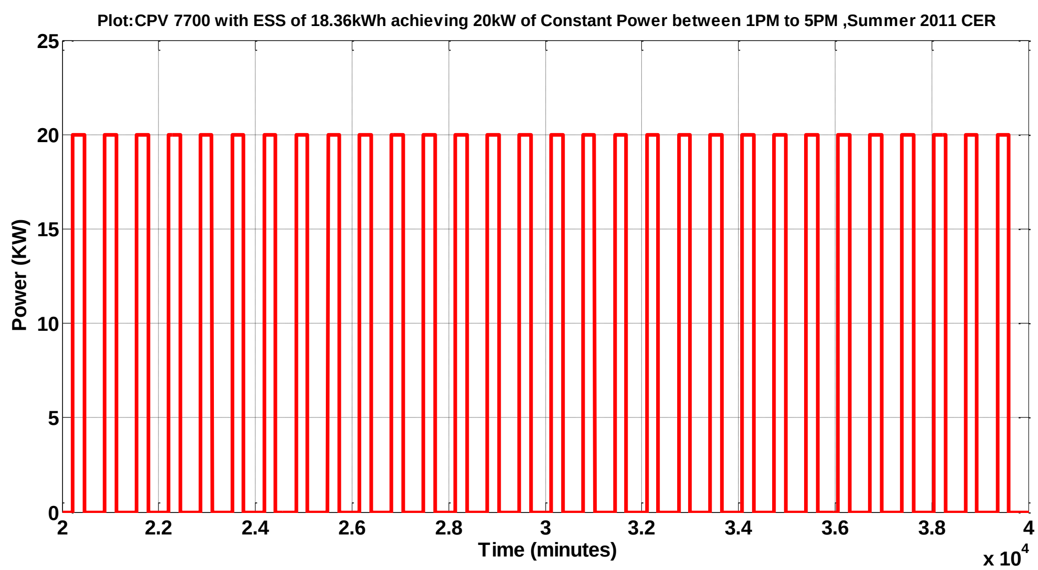

Figure 35 b) Constant 20kW produced based on 18.36kWh ESS, June

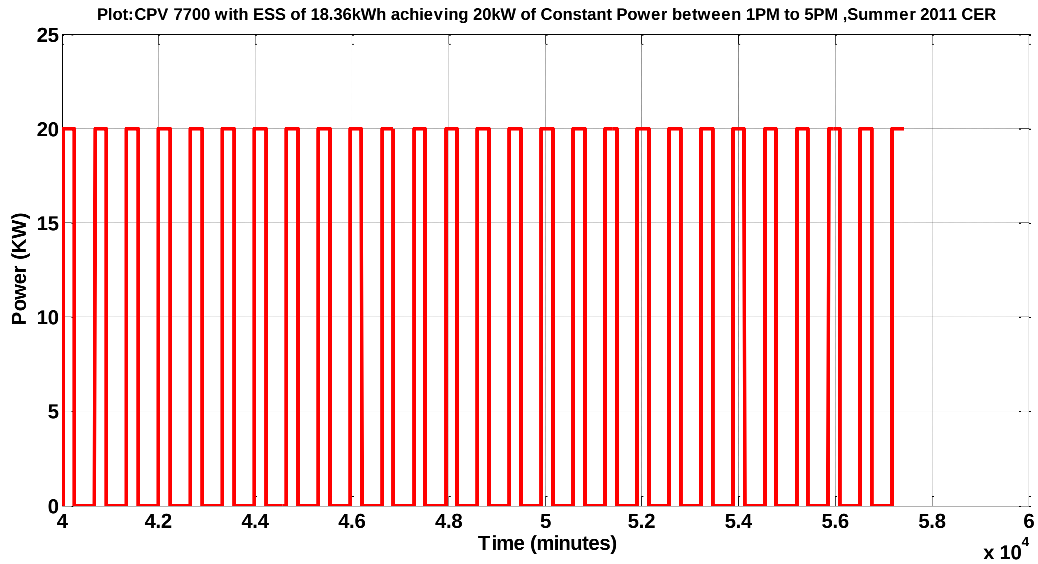

Figure 36 c) Constant 20kW produced based on 18.36kWh ESS, July

5.2.2 Focus on the first few days

As opposed to the previous section whereby a close look was presented in order to magnify the days that the system could not satisfy the demand, this subsection presents a different case. Therefore, since all the days have exhibited the same power distribution pattern portrayed in Figure 37, it would have been a consistent proof to at least put a little emphasis on few days.

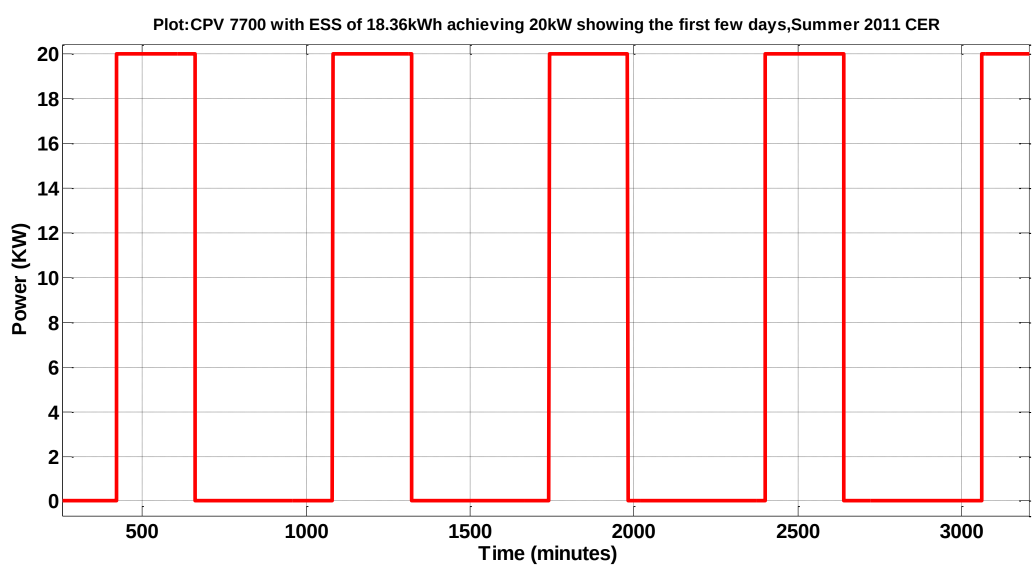

Figure 37 Days showing the pattern

5.2.3 Total energy produced

Figure 38 is the performance curve generated by the system throughout the simulation. The energy is shown to be supplied smoothly throughout the season without any discontinuity.

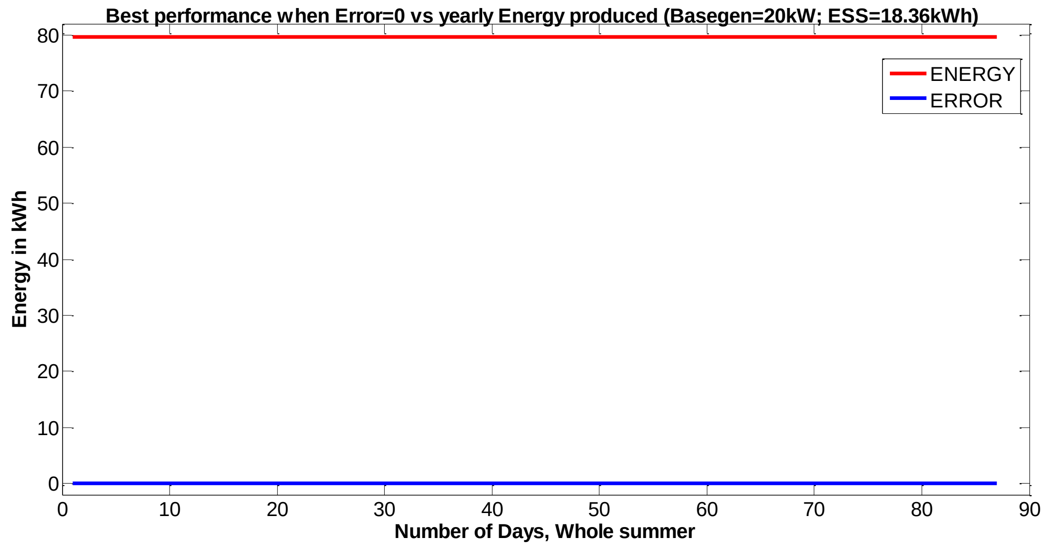

Figure 38 System performance showing a constant energy

5.3 Beyond the size

After reconcilling the theory to the practice, several attempts were made in order to accurately understand the limits and what could happen beyond the limits of the whole system's performance and behavior. Unexpectedly, some surprising results were found which turned out to strengthen the aformentioned statement. Therefore to be able to conduct efficiently the experiments, both the ESS capacity and the base supply generation were set as variables in the sense that while the former varies the latter is kept constant and vice versa. Table 6 gives the summary of all the simulations. In addition to this, an intriguing discovery was that all the power shortage was mainly associated with the 55th and 58th days of the summer season. The plausible explanation may be due to some errors in the data itself otherwise the findings would not make any sense.

Table 6 Simulation Summary

Battery Capacity (kW)	Base Power Supply (kW)	Shortage (kWh) on ith day	Comments
Constant Battery Capacity vs Variable Power Supply			
54 (18.36kWh)	20	zero	Best performance
54	21	55th 0.9696 58th 0.9292	The amount of power shortage increases as the base constant power supplied increases
54	22	55th 2.7061 58th 2.6245	
54	23	55th 4.4594 58th 4.3279	
54	24	55th 6.2325 58th 6.0509	
54	25	55th 8.0108 58th 7.7793	
Constant Power supply vs Variable Battery Capacity			
60	25	55th 6.5511 58th 6.3196	The amount of power shortage decreases as the battery capacity increases.
65	25	55th 5.3347 58th 5.1032	
70	25	55th 4.1183 58th 3.8868	
75	25	55th 2.9019 58th 2.6703	
80	25	55th 1.6854 58th 1.4539	

Hence, as an illustration, Figure 39 a), Figure 40 b), and Figure 41 c) on one hand and Figure 43 a) Figure 44 b) and Figure 45 c) on the other show respectively the day-by-day sample power supply with the following parameters (BaseGen = 21kW, BatCap=54kW/18.36kWh) and (25kW, 54kW/18.36kWh).

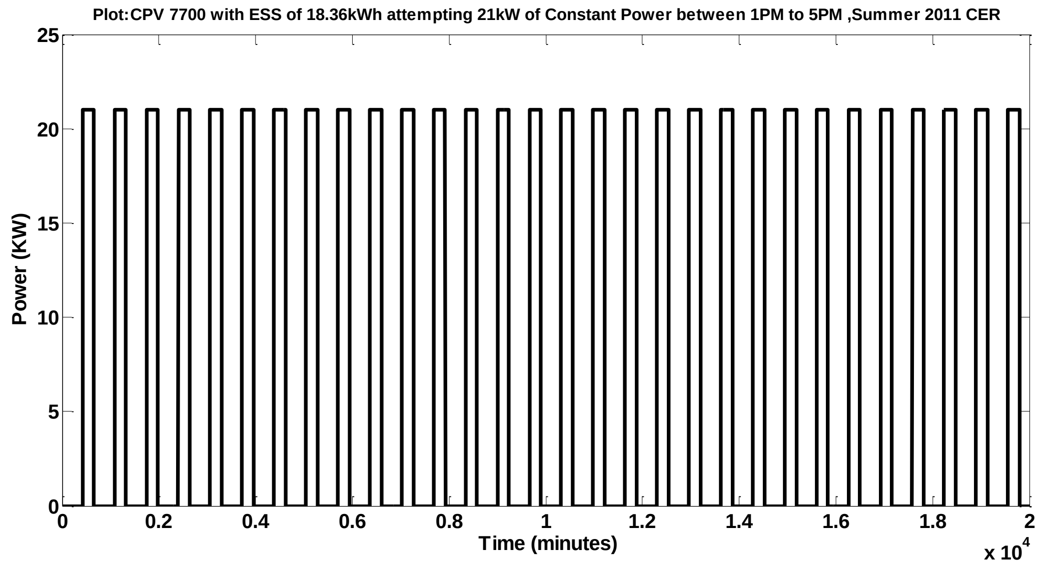

Figure 39 a) 21kW supply with ESS of 18.36kWh, May

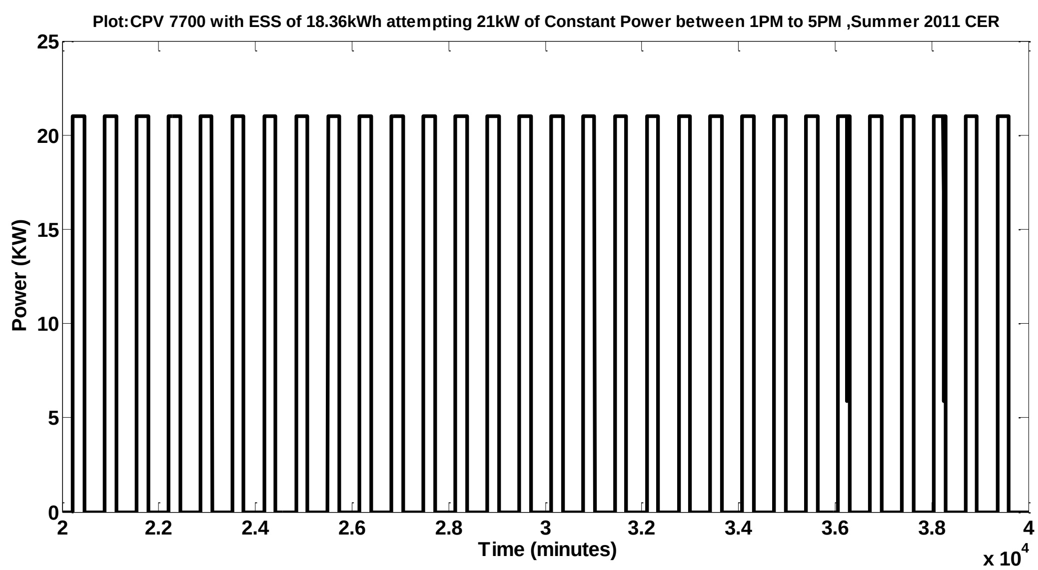

Figure 40 b) 21kW supply with ESS of 18.36kWh, June

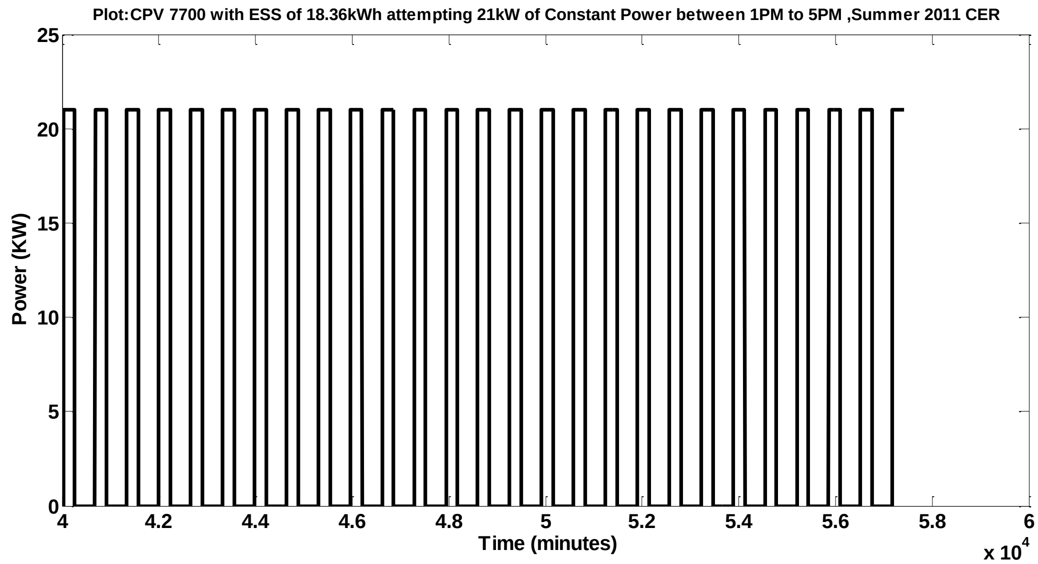

Figure 41 c) 21kW supply with ESS of 18.36kWh, July

In a similar manner to what was done earlier, a focus is presented in Figure 42 d) showing that the system cannot meet the demand for couple of days.

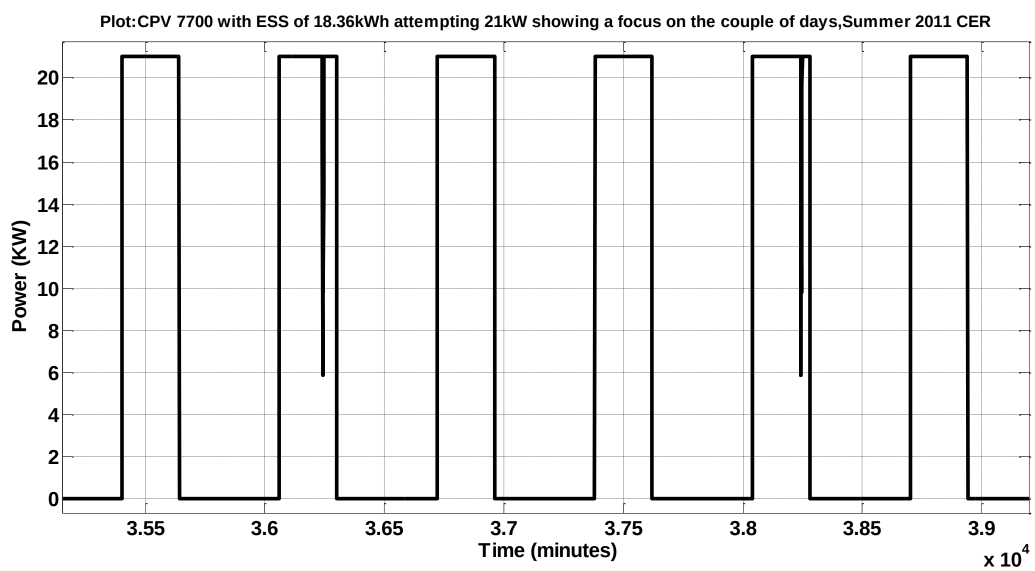

Figure 42 d) Focus on the 2 days of power shortage based on 21kW and ESS of 18.36kWh

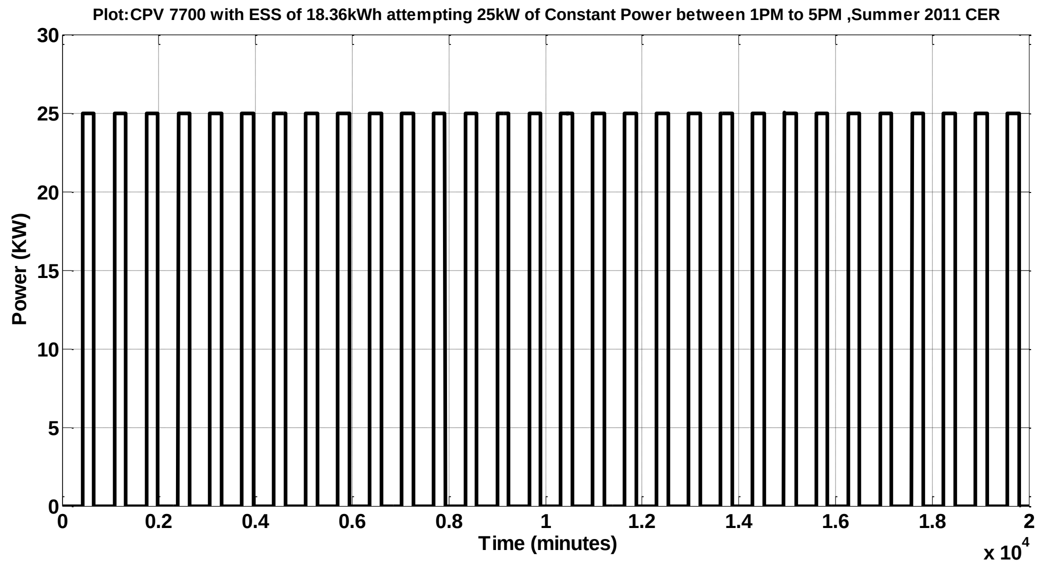

Figure 43 a) 25kW supply with ESS of 18.36kWh, May

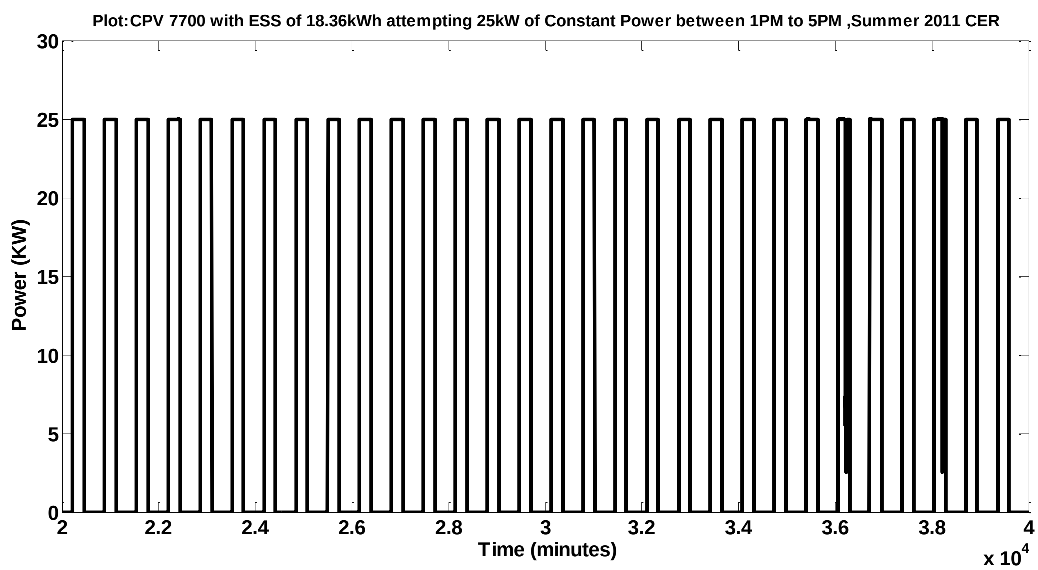

Figure 44 b) 25kW supply with ESS of 18.36kWh, June

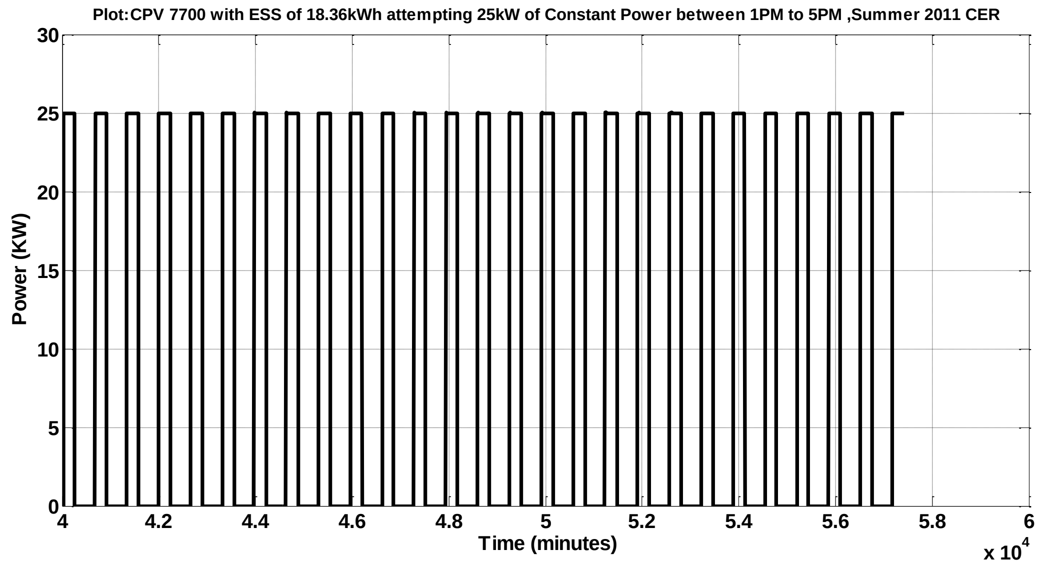

Figure 45 c) 25kW supply with ESS of 18.36kWh, July

5.3.1 Focus on the days for constant 25kW supply versus battery capacity of 54kW

In a similar fashion, Figure 46 depicts closely what would happen if we were to put onto the grid a constant 25kW with the appropriate ESS that matches the CPV unit. The energy distribution is totally even and smooth except for two days that show a slight discrepancy between the generation and the load.

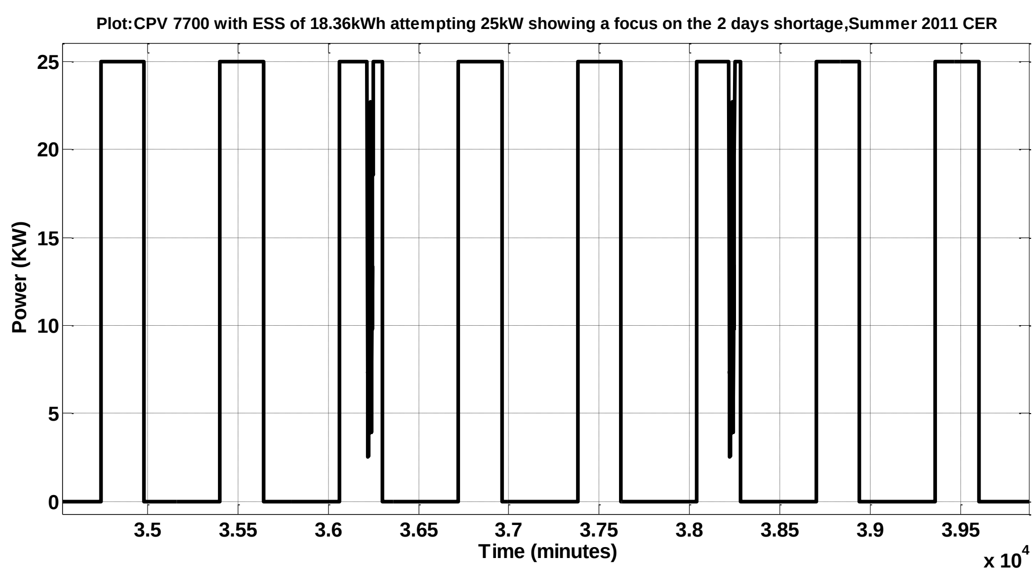

Figure 46 Close look on the two days where Supply < Demand

5.3.2 The total energy production pattern

The total energy produced over the whole summer period is illustrated in Figure 47 showing two holes representing the previous two days that the system cannot satisfy the demand that the utility company may require to shave their peak load. It should be mentioned here that this is just an alternative way of representing the power shortage.

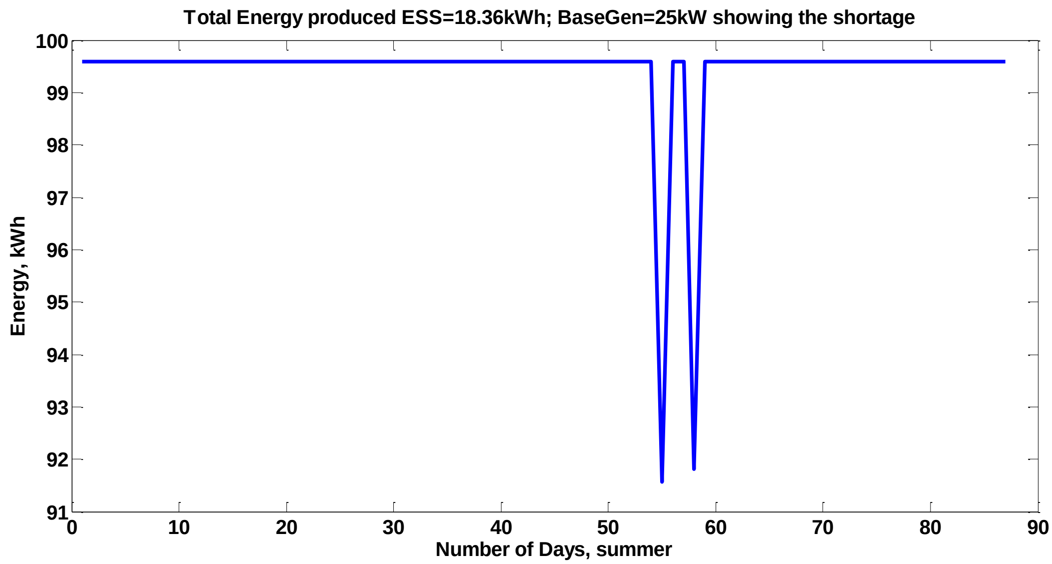

Figure 47 Total Energy produced showing shortage

5.4 The concluding simulation (BaseGen of 25kW, BatCap of 80kW)

As to conclude the discussion, the system seems to show a plateau at 20kW of constant power generated per day. An incremental power step of 5kW was followed in order to arrive at this final significant and meaningful conclusion. The steps are 60, 65, 70, 75 and finally 80kW of increasing ESS capacity. Hence, based on all the previous assumptions with respect to the parameters and if (this did not change at all during the entire simulations) the time step which is the battery discharge time is kept as assumed, the system is only cost-effective at the coordinates (20 base supply; 54 battery capacity), all in kW. The error (which is a measure of how and when the demand is met) in the power shortage goes down each time but never reached zero. In these conditions, it shows an asymptotic behavior by getting closer to zero but never achieving it under the aforementioned circumstances.

Still, with the big battery capacity for this unit, the system can't meet the demand on the 55th and 58th days of the season and the respective power shortages are 1.68kW and 1.45kW. Figure 48 a) through Figure 52 are all related to the last simulation. Where Figure 48 a., Figure 49 b. and Figure 50 c. portray the energy distribution of the whole season. They have been split apart on a monthly basis for clarity purposes. Therefore, since this particular set up in not viable, Figure 51 clearly shows the two days of power shortage. Each of these days has its own specific mark which makes it different from the other.

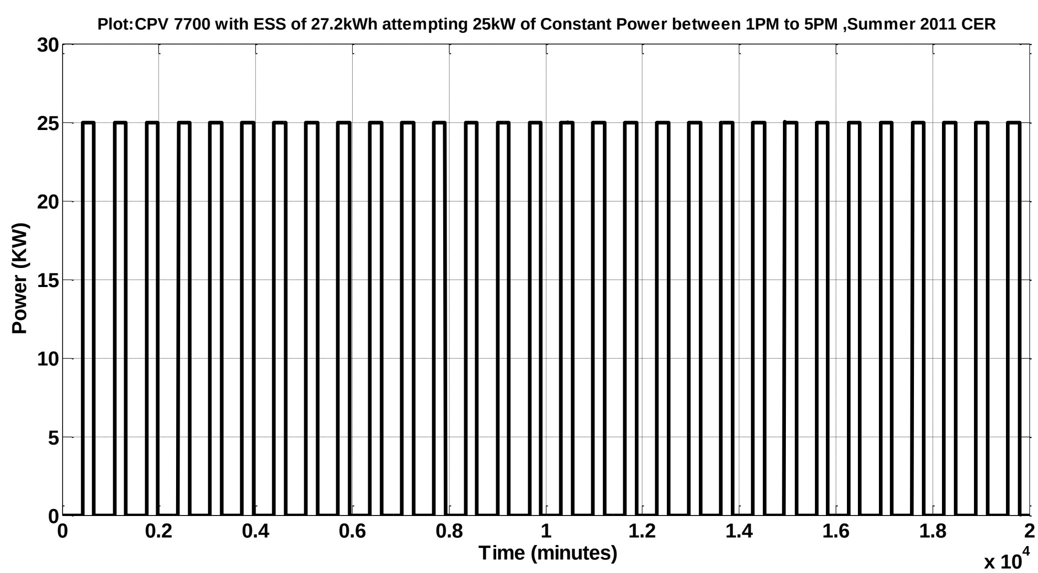

Figure 48 a) Summer daily power distribution, May

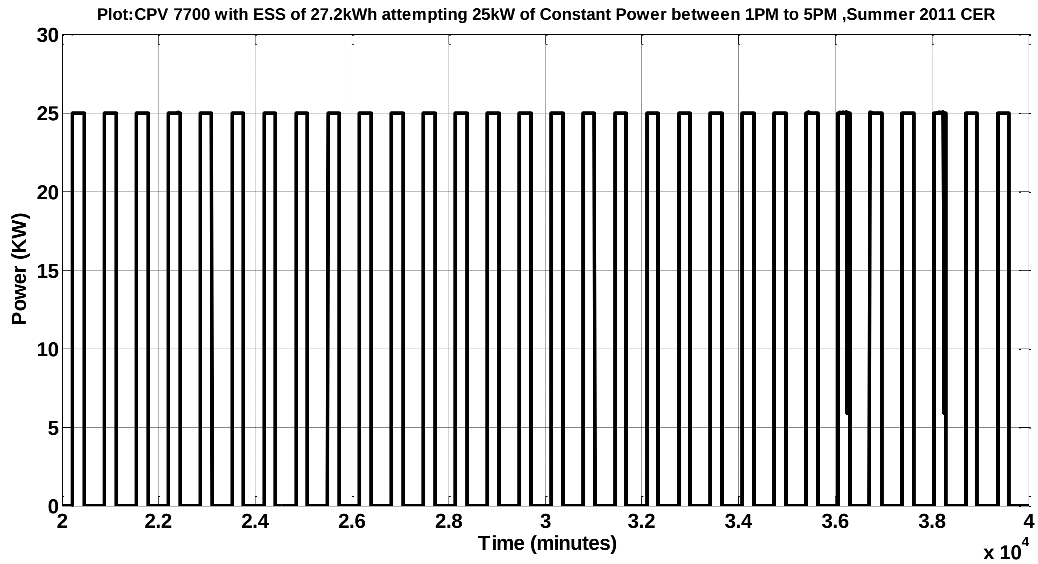

Figure 49 b) Summer daily power distribution, June

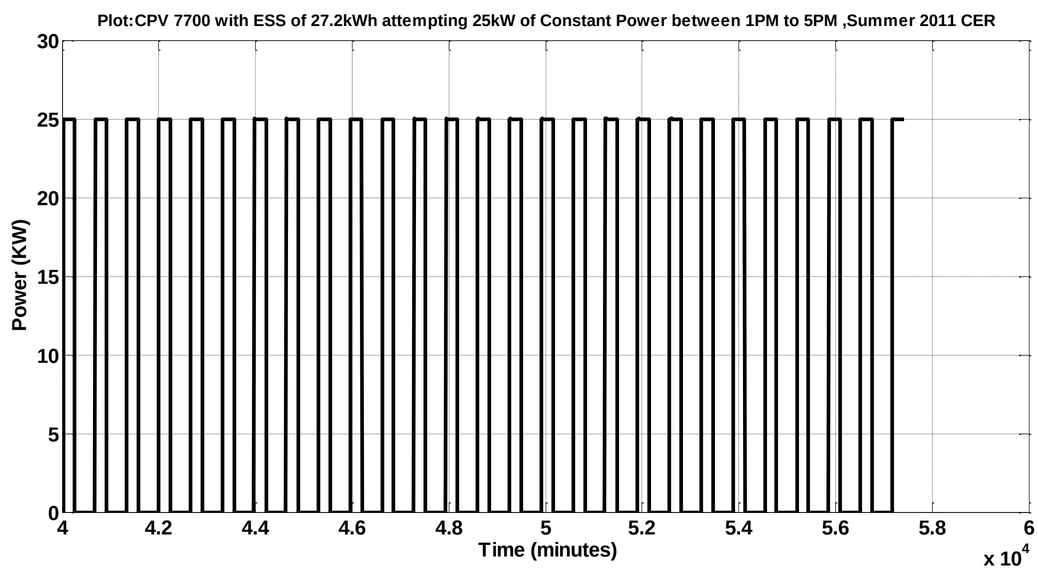

Figure 50 c) Summer daily power distribution, July

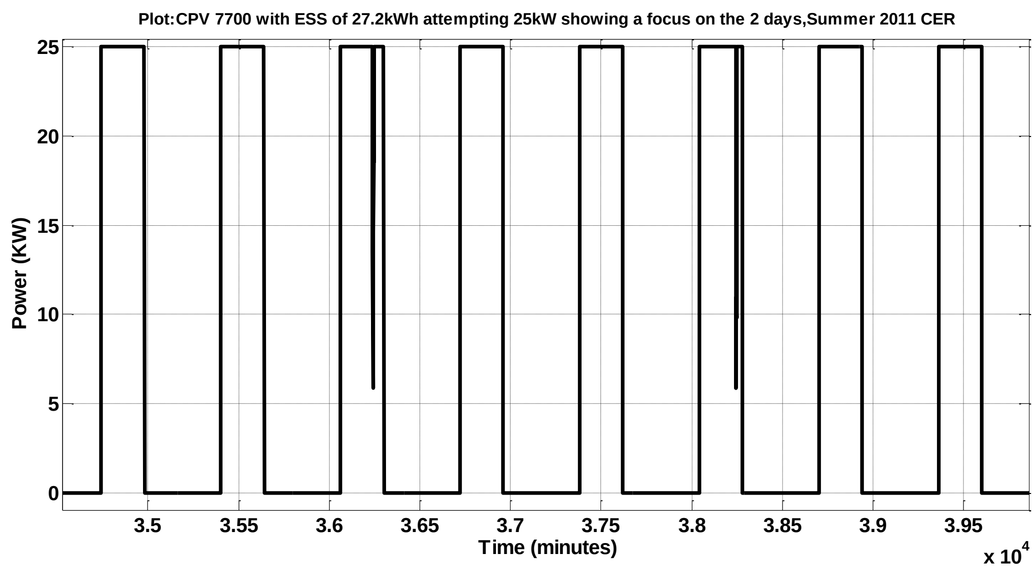

Figure 51 The 55th and the 58th days where the bond would be broken

Finally, Figure 52 depicts a zoom on the 55th day under the same and final conditions set up front with respect to ESS and the CPV system simulations.

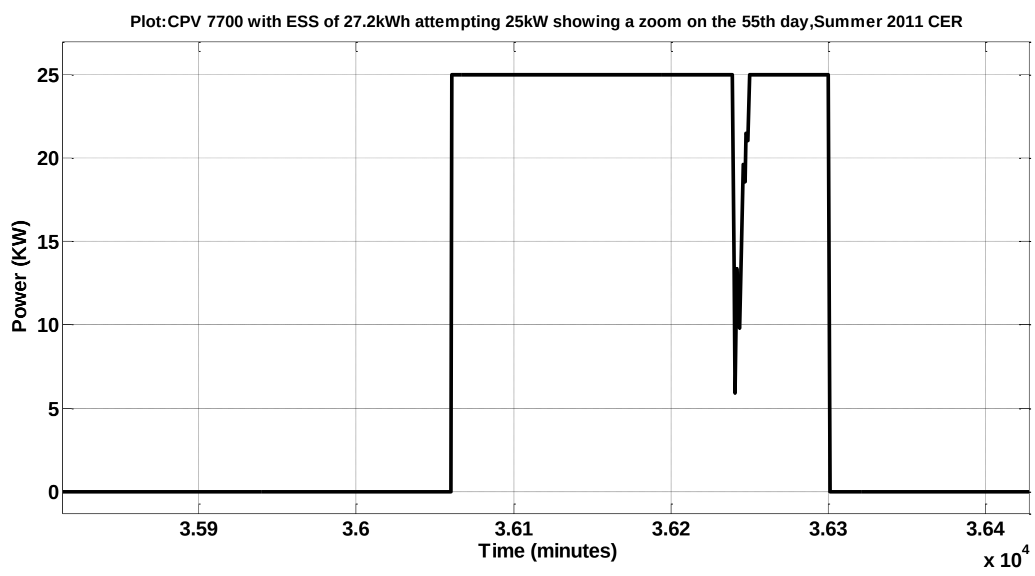

Figure 52 Zoom on the 55th day showing the energy gap

5.5 Is solar a dependable peaking source?

Although this study pertains to a single summer season (2011), it clearly illustrates how CPV can efficiently integrate and fit into NV Energy's power mix. Once again, CPV has shown to have an effective load carrying capability by performing as a reliable load peak shaver. The peak period set by NV Energy authorities begins at 1PM and ends at 7PM. Under these circumstances, the CPV unit in question is able with the help of the backup battery buffer system to supply the utility with a constant 20kW of power and sometimes even more when it is needed.

5.6 Analysis

Having virtually one of the Amonix units tied to the grid with ESS as a backup, shows through this study signs of great advantage. Cases where nearly 50% of each day solar power generation were evaluated can simply be shifted to absorb an equivalent amount of load. This adequate power supply source demonstrates to offset and respond quickly to severe summer peaks by pumping onto the grid a constant amount of power.

Though PV has a great value of firm and reliable power during extreme peak load conditions, in most cases lawmakers have underestimated it. Hence, in this study, substantial evidence is shown by utilizing real CPV data and actual load data from both CER and NV Energy. It is clearly seen that there is a direct link between the available CPV output and the time periods of the day where Nevada inhabitants need an adequate and constant power supply most. The utilization of proper simulation methods (Matlab) helps to demonstrate that the Amonix unit can provide dependable summer peak capacity of +20kW (see Figure **34**) throughout the season. In addition to that, it is not an exaggeration to assert that a constant (25kW) is feasible and is attainable except for two days where the unit is short of few Watts if the discharge time is raised. Therefore, the ultimate correlation to this fact is the amount of CO_2 in the environment that is cut down by reducing the run-time of peaker conventional plants. This shows that Nevada has definitely a high availability of solar resource, which makes it one of the best places in the US to install grid-tied CPVs.

So overall, the system can put onto the grid a constant 20kW per day for the whole summer season from 1PM to 5PM regardless of what could happen during the day based on the previous knowledge of the weather conditions. Hence, for the CPV system of nominal 53kW installed at UNLV, furnishing constant 20kW for the peak demand period is something that could be acceptable.

Additionally, with this kind of system, the average power recorded is sometimes below 25kW due to cloud coverage which makes the results of this study more than realistic in terms of load shifting or peak shaving capabilities. As mentioned earlier, with an energy capacity of 18.36kWh of an ESS coupled to the CPV unit, the results demonstrate that the efficiency in terms of energy and cost-effectiveness is surely somewhere between 15kW and 20kW of constant power supply with a plateau at 20. Beyond this point, the cost of the ESS will be much higher without significantly improving the overall system efficiency. But rather, as the ESS capacity increases drastically, the related errors decrease slightly each time without converging to zero.

CHAPTER 6

6. Economic Analysis

6.1 Characteristics of Energy Storage Devices

6.1.1 Energy Density

It is defined as the amount of energy that can be supplied from a storage technology per unit weight or volume and the equation is as follows:

$$E.D = \frac{\text{Energy Stored}}{\text{Mass or Volume}(\text{m}^3)} \qquad 6.1$$

Where the unit is Wh/kg or Wh/m^3 or J/kg

The energy density can also be defined as the total energy that the storage system can accumulate and deliver with regard to its weight and size.

6.1.2 Discharge Time

The discharge time is defined as the period over which an energy storage system delivers its stored energy. There is an interrelation between the discharge time and the power capability of the system [45]. The power is expressed most of the time either in kW or MW.

6.1.3 Energy Rating

Known as one of the important characteristics of any storage device, the energy rating simply determines how long a device can supply energy. It is either expressed in kWh or MWh. An illustration would be a 200kWh storage system which is rated at 40kW supplies theoretically 40kW of constant power for 5 hours since 200kW=40kWx5.

6.1.4 Costs of Storage systems

Generally quoted in the forms of $/kWh or $/kW, the costs of energy storage devices are often related to the satisfaction of a particular application though some systems will have high cost/kWh of energy, but obviously low cost/kW of power than others or vice versa. It is shown in [45] that the interdependency of the application and its economic feasibility has a lot to do with the aforementioned fact. In addition to that, the market structure which is sometimes uncertain and fluctuating also plays an important role in the economics of a certain types of storage technology. This last characteristic will be further detailed in the next section. It is reported in [44] that despite the fact that some leading battery competitors cost/kWh range from $225/kWh to $300/kWh, the United States Advanced Battery Consortium (USABC) goal is to cut down the cost to $150/kWh for the market to grow. Hence, for that to be done, a major breakthrough has to happen in the field of battery technology as a whole. In fact, it is reported in [51] that the US DOE has set for 2014 the battery prices for PHEV to be sold at $200 to $300/kWh, which seemingly means that the current price range from $500 or $600 to as high as $1100/kWh is still prevalent.

In [53], Nissan has announced the battery pack price to be $375/kWh that later turned out to be a little confusing. The fact is that was the cost at the production level and therefore had nothing to do with the retail cost which in the same source was as high as $750/kWh. Another source [54] stipulated that, in general, chances to get an EV battery less than $450 per kWh are negligible nowadays. Consequently, based on the above trend which has obviously two defined variables (the type of battery technology and the manufacturer), an average value [(minima +maxima) /2] will be assumed in order to keep the sizes versus cost analysis simple and understandable. Table **7** portrays a brief summary of this simplification.

Table 7 Current EV battery cost ranges regardless of the types and the manufacturers

Current EV Battery cost ranges		
1	Maxima	$1100
2	Minima	$450
3	Average	$775

6.2 Battery sizes versus cost analysis

Lithium ion like the other types of batteries considered in this study could be re-used for a variety of applications such as renewable firming. Actually, to cite [32], no one has up to date thoroughly studied the in-and-out of Li-ion second life application. Therefore, from the factory to EV owners and the battery refurbishment companies, lots of data and information are required in order to conduct a comprehensive study. Unfortunately, this is beyond the scope of this thesis. Li-on much like the other storage systems, has an estimated 70 to 80% of its peak power though it can no longer power EVs [32]. To pursue the same thought, EV batteries are said to be ready for their second application whenever they are not capable of providing 80% of their capacity. In addition to that, there are some probabilistic challenges due to the immaturity of the market that are yet to be known.

With reasonable predicted second applications, EV used batteries are undoubtedly a potential source of income for EV owners or battery leasers that they wouldn’t have gotten otherwise and part of the initial cost will thereof be recovered [49].

Fact of the matter is, after being refurbished and resold, that amount of money will be regarded as a salvage value meaning that if LCC analysis is conducted for the second application, there would be zero salvage value. In addition to that, the period of the second analysis will be deducted from the useful life. A simplified instance would be: assume that an EV battery is designed to have 1600 cycles and if happened to be removed after 1000 cycles for whatever reason such as a frequent owner complains due to whatever technical complications, then it would be projected to 600 cycles in its second life and likewise for its energy capacity. However, the probability of the stationary PV storage application is much better for the battery than that in the trunk of an EV car. Hence, by virtue of that, the lifespan of the battery in its second life will be longer than thought.

6.3 Cost of the battery to smooth out the transients

The battery capacity required to smooth the intermittency is approximately 765Ah The energy capacity can then be determined as:

$$E = Ah * V = 765Ah * 24V = 18360Wh = 18.36kWh \qquad 6.2$$

So, with the assumption made above that the EV battery could be purchase at a price of $775/kWh, and then the new EV battery would be purchased at:

$$Total\,cost = \$775 * 18.36 = \$14{,}229 \qquad 6.3$$

That is the price Amonix would pay for each unit if they were to use new batteries to smooth out the intermittencies due to the nature of solar source. But the good news is, in this thesis, that used EV batteries will do that job. Therefore, to be able to do that satisfactorily, assume used batteries are purchased either from EV owners or battery leasers, and that this will cut down the above cost/kWh by half, i.e. $387.5/kWh, which is fairly a reasonable price.

Hence the total cost for the second life utilization would be:

$$Total\ cost = \$387.5 * 18.36 = \$7{,}114.5 \quad 6.4$$

Since there are many unpredictable uncertainties as stated earlier due to the fact that the market is new and anything can happen such as inflation, deflation or a major breakthrough in the science of batteries, consider for the purpose of this analysis that the buy-down price is a variable. A similar analysis is done in [44] for details. The range is assumed to be from $1/kWh to $387.5/kWh. Figure 53 shows the total cost trends of the batteries that are required to eliminate the transients treating the cost per kWh of the used EV batteries as a variable.

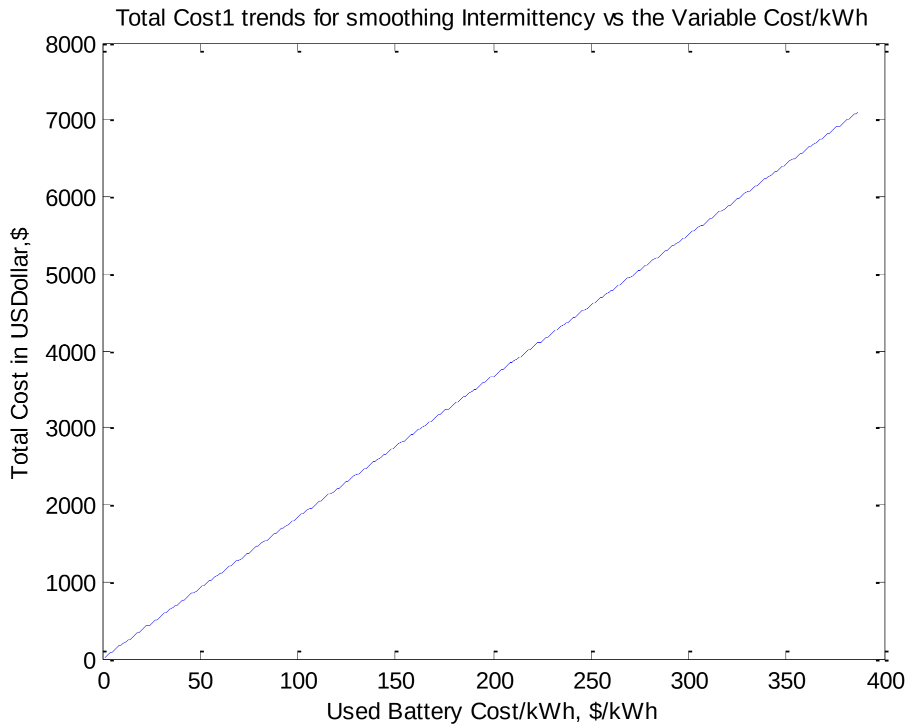

Figure 53 Total cost trends of used EV batteries to level out the CPV 7700 intermittency

CONCLUSION

Conducting a forward-looking research study has never been an easy task but the effort can be valuable to gain new knowledge and be able to arrive at concise conclusions. This was the case here. The intent in this thesis was to come up with a valid proof that would technically lead to a massive penetration of the Amonix CPV 7700 onto the grid with a battery as power backup. The latter would be used to eliminate any transient due to severe weather conditions such as cloud coverage. In this where weather conditions for Las Vegas were used, it was found that with a nominal rating of 53kW of power, the Amonix unit is able to produce up to 42kW of maximum power output on a daily basis. So, with that in mind, the ESS of a capacity of 54kW(18.36kWh), not only is able to smooth out any power transient, but also is capable of putting onto the grid a constant power of 20kW throughout the summer season during the peak period of the day without any interruption. Therefore, the study was conducted as follows:

- The simulations started with a base power of constant 15kW with an ESS of 30kW; that turned out to be possibly acceptable but not totally sufficient.
- Step-by-step simulations were carried out with an increment of 5kW until a satisfactorily conclusion was reached whereby the simulation findings matched the calculated values (constant 20kW of power put onto the grid for an energy capacity of 18.36kWh).
- Estimates of the cost-effectiveness of this approach with current ESS prices were not positive. However, it could be cost effective if ESS battery pack prices drop to $375/kWh [53].
- It would be desirable to perform an experiment on an actual system to see if the estimates made here would be reasonable.

Hence, as opposed to the current major sources of energy used across the world, photovoltaic in particular and renewable in general is surely the way out to cut down our CO_2 emission which is one of the sources of the recent GW. Admitting CPV to our energy midst would also lead to clean air and water for the whole mankind especially the innocent ones who have nothing to do with the problem of climate change due our legendary habit of energy consumption.

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APPENDIX A

ABBREVIATIONS AND ACRONYMS

AGC = Automatic Voltage Control

AGM = Absorbent Glass Mat (Maintenance-free Battery)

BaseGen = Constant power generated by the unit (CPV 7700 + ESS)

BOS = Balance of System

CB = Circuit Breaker

CER = Center for Energy Research

CPV = Concentrated Photovoltaic

CSV = Concentrated Solar Power

DNI = Direct Normal Incidence

DOD =Depth of Discharge (%)

E = Energy the CPV 7700 Can Deliver

ED = Energy Density

EME = Electromagnetic Energy

ESS = Electricity Storage Systems

EV = Electric Vehicle

FF = Fill Factor

HCPV = High Concentration Photovoltaic

LAB = Lead-acid Battery

Lib = Lithium Ion Battery

MPP = Maximum Power Point

MPPT = Maximum Power Point Tracker

Ni-Cad = Nickel Cadmium

P = Power that the CPV 7700 can deliver

PHS =Pumped Hydro Storage

RE = Renewable Energy

RT = Room Temperature

SC = Single Crystal

STC = Standard Testing Conditions

T = Discharge time

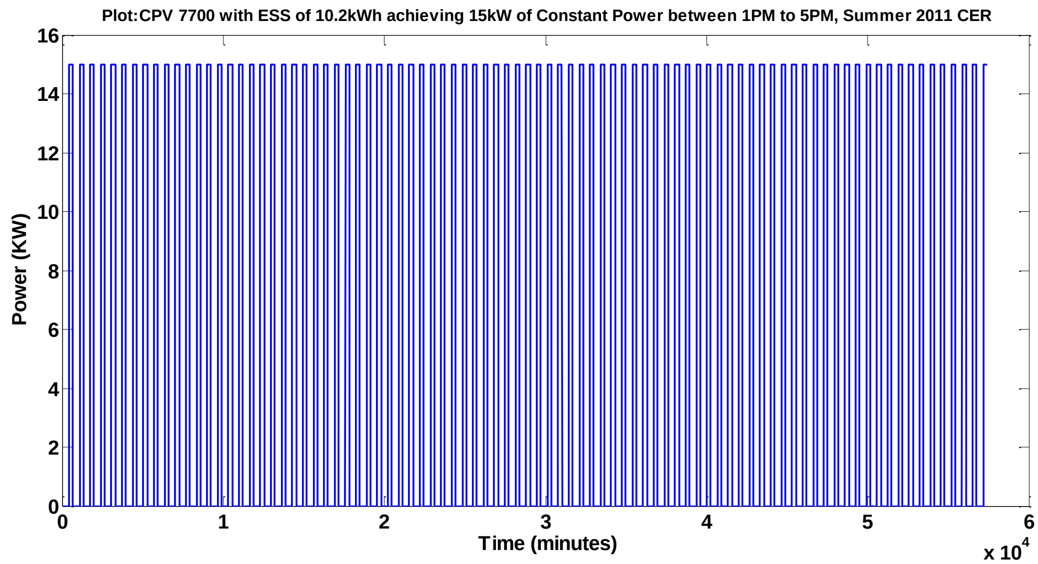
UC = Ultra-Capacitor

USABC = United States Advanced Battery Consortium

APPENDIX B

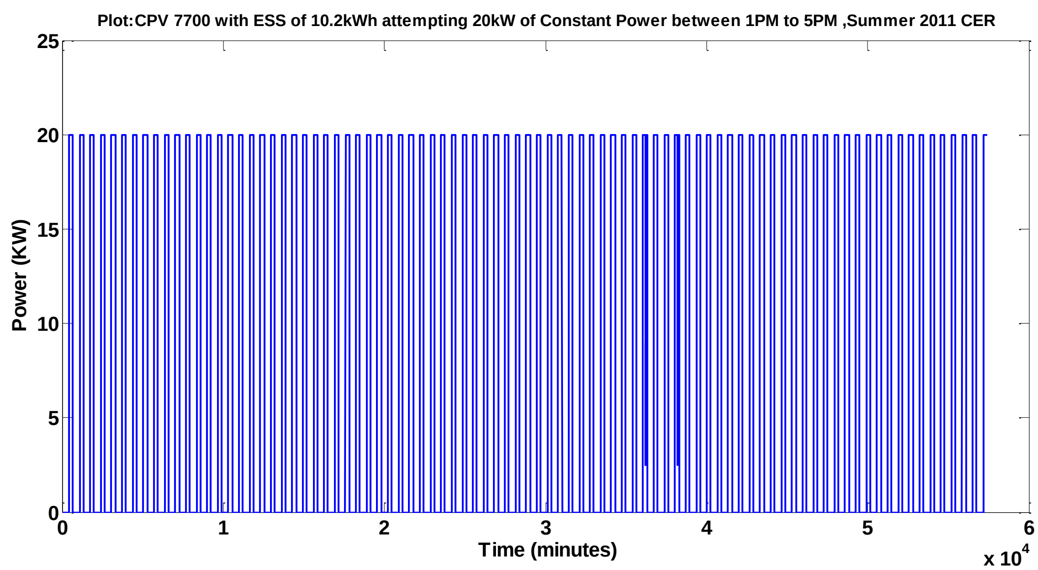
1. System CPV 7700 + ESS of 10.2kWh (power=30kW)

Achieves constant 15kW for the whole summer; this is ok but not enough



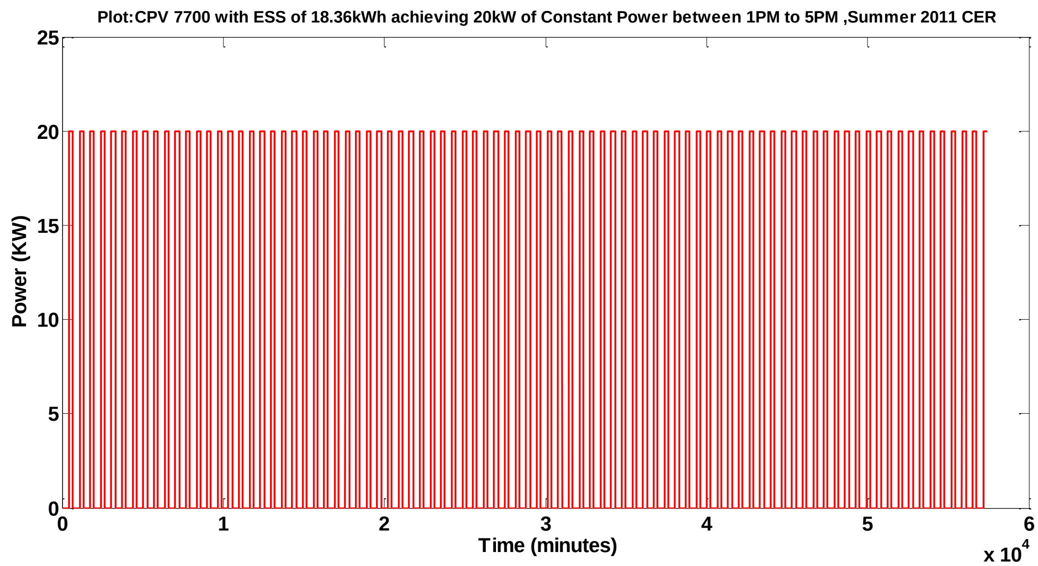
2. System CPV 7700 + ESS of 10.2kWh (power=30kW)

Attempts constant 20kW for the whole summer; this is not feasible base on these parameters

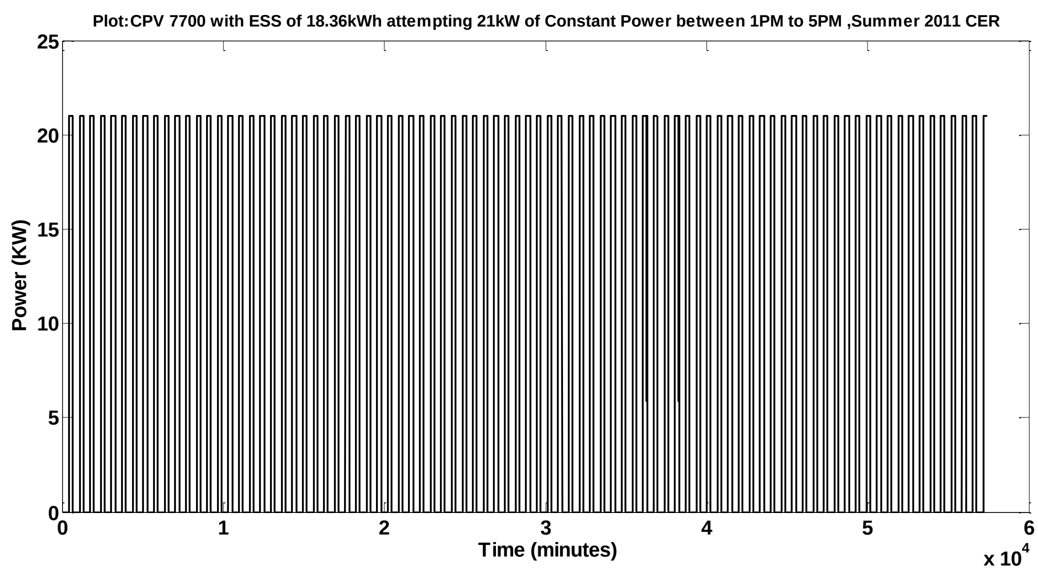


3. System CPV 7700 + ESS of 18.36kWh (power=54kW)

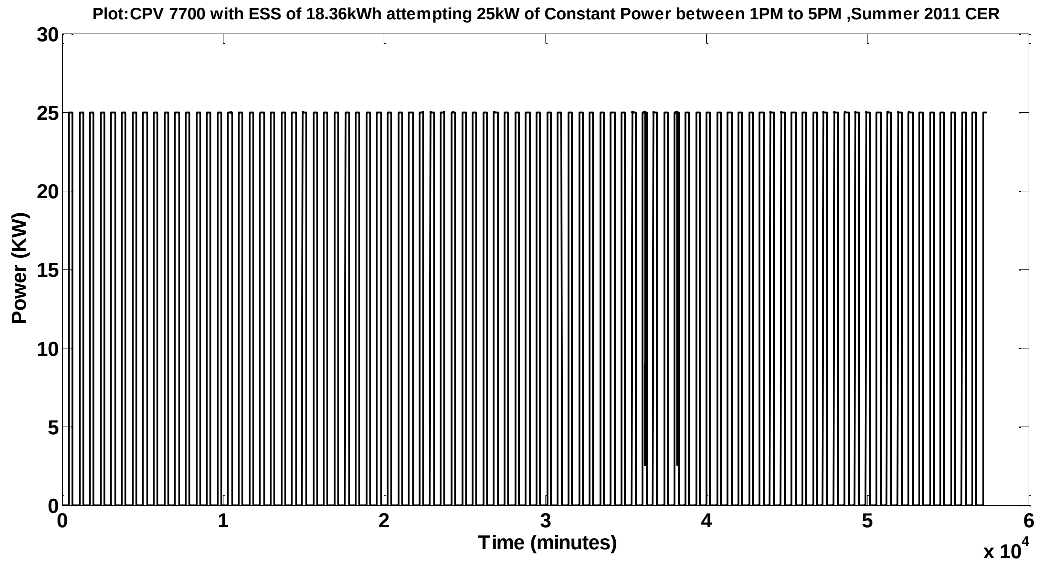
Achieves constant 20kW for the whole summer. The calculated values as well as the simulated results proved the viability of this project.



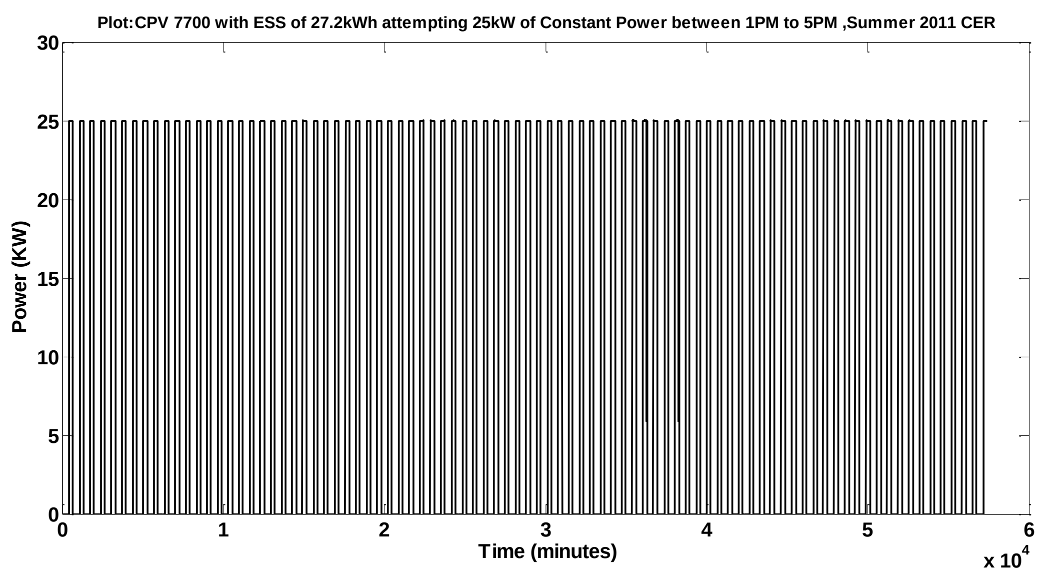
4. Whole summer period: Base CPV power=21kW; ESS=18.36kWh



5. Whole summer period: Base CPV power=25kW; ESS=18.36kWh



6. Whole summer period: Base CPV power=25kW; ESS=27.2kWh
The corresponding battery capacity is equal to 80kW.



APPENDIX C

1. Code for economic analysis

```
clear all
close all
P_usedBat = 1:387.5;     % the price is in US Dollar
E_capIntermittent = 18.36;  % [kWh]Required Energy to smooth out power
transient is constant
T_cost1 = P_usedBat*E_capIntermittent;

%%%
E_CapLoadShift = 110.16;% [kWh] Required for shifting the planned
constant Load
T_cost2 = P_usedBat*E_CapLoadShift;


figure
plot(P_usedBat, T_cost1)
xlabel ('Used Battery Cost/kWh, $/kWh')
ylabel ('Total Cost in USDollar,$')
Title ('Total Cost1 trends for smoothing Intermittency vs the Variable
Cost/kWh')

figure
plot(P_usedBat, T_cost2)
xlabel ('Used Battery Cost/kWh, $/kWh')
ylabel ('Total Cost in USDollar,$')
Title ('Total Cost2 trends for load Shifting vs the Variable Cost/kWh')
```

2. Code for ESS sizing and simulations

```
%THESIS: BUFFERING PV OUTPUT DURING CLOUD TRANSIENTS WITH ENERGY
STORAGE
%
clear all
clc
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%
% INPUT
%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%% Import data
%-----------------------------------------------------------------------
----
%%
[NUM STR] = xlsread('Summer Data.xls','Summer');    % summer(June -Aug)
TIME = NUM(:,1);% time as a serial number measured from 12:00AM
time = datestr(TIME);% time converted to HH:MM (AM/PM)
PV = NUM(:,2);
NetPower = NUM(:,3);
DATE = STR(:,1);

MaxPV = max(PV);
```

```
AvgPV = mean(PV);
%
% Battery Characteristics
dschgTime =0.34;        %[hr] assumed storage discharge time @ max power
capacity
BatPwrCap_max = 54;     %[kW]  maximum power capacity of battery storage
BatEnergyCap_max = dschgTime*BatPwrCap_max;  %[kWh] max energy capacity
BatEnergyCap_min = 0.2*BatEnergyCap_max;
%
eff_cycle = 0.8;                 % cycle/round trip efficiency
eff_c = sqrt(eff_cycle);         % charging efficiency(assumed to be
same as discharge eff.)
eff_d = sqrt(eff_cycle);         % discharging efficiency
%
BatEnergyCap_old=BatEnergyCap_min;  % i.e at initial time or t=t-1
%
% Time Step
TimeStep=1/60; %[hr]  % the data is in 1min interval
%
% Dispatch period
peakStart = 7; %[7am=1, 8am=2,.....5pm=11]
% peakEnd = 11
%
for n=1:87      % number of days in summer
    for k=1:11         % no of day sun hours
        for j=1:60     % no. of mins
            %
             i=(11*(n-1)+(k-1))*60+j; % conversion from day to hour
then to minute
            %
            if k<=peakStart      % Off peak time operation
               BasePVGen=0; %[kW]
               Mismatch(i,1) = PV(i)-BasePVGen;    % units of power [kW]
               if Mismatch(i)>=0
                   BatDischarge(i)= 0;
                   pulseDisch(i) = 0;
                   DischLoss(i) = 0;
                   if BatEnergyCap_old == BatEnergyCap_max  % if the
battery is fully charged
                       BatCharge(i)=0;
                       pulseCh(i) = 0;
                       ChgLoss(i) = 0;
                       BatEnergyCap_new = BatEnergyCap_max;
                   else
                       BatCharge(i)=eff_c*Mismatch(i);
                       pulseCh(i) = 1;
                       ChgLoss(i) =(1-eff_c)*Mismatch(i);
                       if BatCharge(i)>BatPwrCap_max % when we have
more than could be put into the battery at any time step
                          BatCharge(i)=BatPwrCap_max;
                          ChgLoss(i) =((1-eff_c)/eff_c)*BatCharge(i);
                       end
                         BatEnergyCap_new = BatEnergyCap_old +
BatCharge(i)*TimeStep;  % units of energy [kWh]
                       if BatEnergyCap_new > BatEnergyCap_max
                          BatCharge(i)= BatCharge(i)-((BatEnergyCap_new
- BatEnergyCap_max)/TimeStep); % units of power [kW]
```

```
                        ChgLoss(i) =((1-eff_c)/eff_c)*BatCharge(i);
                        BatEnergyCap_new = BatEnergyCap_max;
                     end
                 end
             end  % end of off-peak
            %
           else  % On peak
              BasePVGen=25;  % constant power put onto the grid at
peak time
              Mismatch(i,1) = PV(i)-BasePVGen;   % units of power [kW]
            %
             if Mismatch(i)>0   % charging of battery
                 BatDischarge(i)= 0;
                 pulseDisch(i) = 0;
                 DischLoss(i) = 0;
                 if BatEnergyCap_old == BatEnergyCap_max  % if the
battery is fully charged
                     BatCharge(i)=0;
                     pulseCh(i) = 0;
                     ChgLoss(i) = 0;
                     BatEnergyCap_new = BatEnergyCap_max;
                 else
                     BatCharge(i)=eff_c*Mismatch(i);
                     pulseCh(i) = 1;
                     ChgLoss(i) =(1-eff_c)*Mismatch(i);
                     if BatCharge(i)>BatPwrCap_max
                        BatCharge(i)=BatPwrCap_max;
                        ChgLoss(i) =((1-eff_c)/eff_c)*BatCharge(i);
                     end
                       BatEnergyCap_new = BatEnergyCap_old +
BatCharge(i)*TimeStep;  % units of energy [kWh]
                     if BatEnergyCap_new > BatEnergyCap_max
                        BatCharge(i)= BatCharge(i)-((BatEnergyCap_new
- BatEnergyCap_max)/TimeStep); % units of power [kW]
                        ChgLoss(i) =((1-eff_c)/eff_c)*BatCharge(i);
                        BatEnergyCap_new = BatEnergyCap_max;
                     end
                 end

               elseif Mismatch(i)<0  % start discharging battery to
meet the BasePVGen
                     BatCharge(i)= 0;
                     pulseCh(i) = 0;
                     ChgLoss(i)= 0;
                     %
                      BatDischarge(i)= abs((eff_d^-1)*Mismatch(i));
% the abs. makes the discharge values +ve
                      pulseDisch(i) = -1;
                      DischLoss(i) =(1-eff_d)*BatDischarge(i);
                      %
                  if(BatEnergyCap_old-
(BatDischarge(i)*TimeStep))>=BatEnergyCap_min  % enough to supply
                      DischLoss(i) =(1-eff_d)*BatDischarge(i);
                      BatEnergyCap_new = BatEnergyCap_old -
(BatDischarge(i)*TimeStep);
                      %
```

```
                    elseif(BatEnergyCap_old-
(BatDischarge(i)*TimeStep))<BatEnergyCap_min  % deficit in supply but
can supply part
                        BatDischarge(i)=(BatEnergyCap_old-
BatEnergyCap_min)/TimeStep;
                        DischLoss(i) =(1-eff_d)*BatDischarge(i);
                        BatEnergyCap_new = BatEnergyCap_old -
BatDischarge(i)*TimeStep;
                    else   % deficit in supply and can't supply any
                        BatDischarge(i)= 0;
                        pulseDisch(i) = 0;
                        DischLoss(i)= 0;
                        BatEnergyCap_new = BatEnergyCap_old;
                    end
                 %
              else %(i.e Mismatch(i)==0)
                    BatCharge(i)= 0;
                    pulseCh(i) = 0;
                    ChgLoss(i)= 0;
                    BatDischarge(i)= 0;
                    pulseDisch(i) = 0;
                    DischLoss(i)= 0;
                    BatEnergyCap_new = BatEnergyCap_old;
              end
            end
            %%%%%%%%%%%%%%%%%%%%%%%%%%%%
            if Mismatch(i)>=0
               SysOutput(i,1)=BasePVGen;
            else
               SysOutput(i,1)=PV(i)+BatDischarge(i)-DischLoss(i);
            end
            %
            baseGen(i,1)=BasePVGen;
            batcap(i,1)=BatEnergyCap_new;
            batChg(i,1)=BatCharge(i);      % battery charging
            batDisChg(i,1)=-BatDischarge(i);    % battery discharging
            pulseCharg(i,1) = pulseCh(i);           % charging pattern
            pulseDischarg(i,1) = pulseDisch(i);     % discharging
pattern
            chargeLoss(i,1)= ChgLoss(i);           % charge losses
            dischargeLoss(i,1)=-DischLoss(i);     % discharge losses
            %
            BatEnergyCap_old = BatEnergyCap_new;   %[kWh]
            %
         end
    end
end
%
BatSize = max(BatEnergyCap_new);
%
TotalChgEnergy = sum( batChg);
TotalDschEnergy = sum(batDisChg);
TotalChgLoss = sum(chargeLoss);
TotalDischLoss = sum(dischargeLoss);


%% Plot and Represent Data
```

```matlab
close all
n = length(SysOutput); % total length of data
A = SysOutput==0;% find when there no data recorded (when battery
charges between 6AM to 1PM)
B = find(A==1);% select these data points for the whole season
C = 1:n;
C(B) = [];% eliminate these zero readings

% mark the beginning of days
D = C(1);
for i = 1:length(C)-1
    if (C(i+1)-C(i))>1

        D = [D C(i) C(i+1)];
    end
end
D = [D C(end)];

BEGIN = D(1:2:end);
END = D(2:2:end);

for i = 1:length(BEGIN)
    Reading(:,i)= SysOutput(BEGIN(i):END(i)); % get the readings per
minute
    E(i) = trapz(Reading(:,i))/60;% integrate the readings to find
losses/increases
    % we divide by 60 to get hours
end
AVERAGE = 25*(D(2)-D(1))/60;
ERROR = E - AVERAGE; % When the system meets the contract this quantity
is zero; otherwise it's -ve #
figure
plot(SysOutput)
xlabel('\bf Time (minutes)','FontSize',14)
ylabel('\bf Power (KW)','FontSize',14)

figure
plot(E)% plot the integrated readings
xlabel('\bf Number of Days','FontSize',14)
ylabel('\bf Energy (KWH)','FontSize',14)
% plot(PV)
```

VITA

Graduate College
University of Nevada, Las Vegas
Yacouba Moumouni

Degree:

Bachelor of Engineering, Electrical and Computer Engineering, 2003
Federal University of Technology, Minna, Nigeria

I presented at the 9th Annual **IEEE** Consumer Communication & Networking Conference, **CCNC 2012** held in Las Vegas, Nevada USA (January 14-17, 2012) the paper:

- ✓ Performance Analysis of Decode-and-Forward Multi-Hop Transmission for Vehicular Networks
- ✓ Autors : Mohamed Fathy et al. Electrical and Computer Eng., University of Wterloo, Ontario, Canada, N2L 3G1

Thesis Title: **BUFFERING PV OUTPUT DURING CLOUD TRANSIENTS WITH ENERGY STORAGE**

Thesis Examination Committee:

Chairperson, Robert Boehm, Ph. D.
Committee Member, Woosoon Yim, Ph.D.
Committee Member, Yitung Chen, Ph.D
Graduate Faculty Representative, Yahia Baghzouz, Ph. D.