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The Effect of Storing Produced PV Power on the National Grid

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ABSTRACT

The dramatic increase in renewable sources employment and the new trend to eliminate carbon emissions are the main reasons for using energy storage to overcome the fluctuation of Photovoltaic (PV) output. This paper aims to study the ability of PV solar system, to provide a significant fraction of utility systems energy demand in Jordan. MATLAB software was used to simulate algorithms in order to estimate the storage properties of Energy Capacity (EC), Power Capacity (PC), and Capacity Ratio (CR). These properties are mainly affected by the size of the PV system and the flexibility (*ff*) of the grid. The hourly generation data from the National Electric Power Company (NEPCO) were investigated to determine the most efficient way to feed PV-generated power into the grid.

It was found that for flexibilities (*ff*) values of 0.7, 0.8, and 1, the No-Dump (ND) PV system, which is the largest PV system that could deliver all its annual production to the grid without any need of spillage of the PV system size were 566.3MW, 998.4MW and 1.6 GW respectively.

Also, the relation between Energy Capacity of storage (EC) and Power Capacity (PC) was investigated, it was found that if storage installed with EC and PC equal to 24 GWh (almost 45% of average daily demand) and 3 GW (which is less than the peak hour demand) at *ff*=0.8, the penetration of PV energy will increase by 42% of annual demand compared with almost 10% without storage. Furthermore, if *ff* is increased to 1 in parallel to installing storage with energy capacity and power capacity equal to 52.7 GWh and 4.7GW, respectively, the PV penetration will increase to reach 68% of the annual demand compared to 16% without storage.

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1. Introduction

In PV systems, there is surplus energy during sunny hours that could not be sent into the grid immediately. This energy could be harnessed to be used during low or no solar power generation. This would be the best utilizing of the available solar radiation while available.

Denholm and Margolis (2007) investigated how some technologies could help in increasing penetration and eliminate unused PV energy. They performed a simulation of a large utility system using hourly isolation data and load data [1], they found that the system has extra PV generation during certain periods of the year under high penetration levels of PV systems and existing grid operations and rules. Further, they examined the excess PV generation and the resulting costs as a function of PV penetration at different levels of system flexibility. This is achieved by developing several metrics and using a PV load model (Pvflex) [2] to examine the possible influences of large PV employment.

Ibrahim *et al*. (2008) examined the various power storage solutions based on key criteria, concluding that while storage is now expensive, it may become unavoidable in the future [3]. Chen *et al*. (2009) studied the capital cost factor of energy storage technologies and other factors like power rating and discharge time and demonstrated many storage varieties [4].

A. Zahedi (2010) concluded that energy storage technology would play a significant role in increasing the reliability of solar power generation systems. He reviewed the issues in relation to grid integration of solar PV systems and a range of storage devices that could theoretically and economically be used in link with solar PV energy in order to increase the solar energy penetration level. Finally, he presented a model for a solar PV system joined with a battery and super-capacitor [5].

Solomon *et al*. (2012) studied the available storage technologies, and defining the appropriate storage size to match large PV energy to the grid, and examined the definition of Usefulness Index. They demonstrated that hybrid storage could be used to achieve suitable characteristics [6].

Denholm and Hand (2011) performed Simulations in the Texas, US (ERCOT) grid, in which they concluded from simulation results that the penetration could level up to 80% of the system's electricity demand keeping curtailments to less than 10%. This requires a combination of load shifting and storage equivalent to about one day of average demand [7].

Aldo *et al*. (2013) presented in their study the effect of the load mismatch on energy and how the existence of the load mismatch can affect the prices of purchasing electricity from the grid plus the amount of surplus electricity generated by a great number of PV systems may cause a major problem for the grid operators [8].

Solomon *et al*. (2014) conducted a technical and economic examination of the results of hourly simulations using hourly load data and the simulated production of wind and solar technologies across California. Also, they examined how to increase energy penetration from the renewable system into the electricity grid. Finally, they underlined the importance of considering the physical and operational policy scenarios of the future in designing an efficient and least-cost grid [9].

Solomon *et al*. (2015) performed a study using one-year hourly demand data of California's electricity grid together with the hourly-simulated output of various solar and wind technologies distributed throughout the state. The result shows that wind-solar complementarities carry significant multidimensional benefits to the future grid as compared to a stand-alone wind/solar-based grid [10].

Ould *et al*. (2016) presented a summary of energy storage in renewable energy systems and underlined the role of storage in keeping a strong and reliable current electricity system and developing the electric system flexibility. They focused on hydrogen, flywheel, and batteries storage used in renewable energy systems like photovoltaic and wind power plants. They used MATLAB software to study the performance of battery and flywheel storage systems in photovoltaic and wind energy applications [11].

Mukrimin *et al*. (2017) discussed the side effects on power grid systems from generating energy from renewable energy sources. Also, they presented an inclusive description of energy storage systems with comprehensive classification, advantages, environmental influences, and implementation possibilities with application variants [12].

Hemmat *et al*. (2017) presented optimum planning and scheduling on energy storage systems (ESSs) to manage electric power systems containing renewable energy resources. They found the optimal capacity and charging-discharging features of ESSs, and they demonstrated that future planning could manage congestion of the network efficiently while dealing with wind and solar resources uncertainties [13].

Sun *et al*. (2020) discussed the importance of hybrid energy storage in smoothing the output fluctuation of renewable energy, effectively improving the grid-connected permeability and capacity credibility of renewable energy. They also mentioned that the total installed capacity of global energy storage projects in operation was 175.4 GW, an increase of 4% year on year, and the growth rate was stable [14].

Yousif *et al*. (2019) studied large-scale electric grid systems (26 GW) supplied by renewable energy sources (wind turbines, solar photovoltaic) with energy storage systems (electrochemical storage, fuel cell, battery). It was found that the least cost combinations require excessive generation capacity, diverse renewable generation resources, and energy storage techniques, which would meet the load requirements and have fewer carbon emissions [15].

Solomon (2019) mentioned that: matching, variability and uncertainty are the most important challenges of large-scale PV penetration. To overcome these challenges, many techniques could be used, such as energy storage, demand response, increased grid flexibility, improved forecasting [17].

Daniel-Ioan Stroea *et al*. (2018) Studied the power and energy management strategies for a hybrid residential PV – wind system with Li-ion battery storage. The needed data was taken from the Danish market by using real generation profiles (i.e., irradiation and wind speed) plus the load profile. The behavior of the hybrid energy system was studied for power smoothing and energy blocks applications for two scenarios (i.e. a summer day and a winter day) [18].

Nge *et al.* (2019) presented a real-time energy management system (EMS), which maximizes the total output for the PV/battery system that connects to a smart grid with the change in electricity prices. The proposed reactive real-time control technique needs only forecasting the average PV power output over the total optimization interval [19].

Freeman *et al*. (2016) mentioned that at penetration levels above 15–30% in isolated grids, on-dispatch-able generation sources like P.V. solar or wind turbines would basically need electrical energy storage systems and higher generation flexibility. These adjustments would be needed to buffer the irregularity of Wind and Solar and to match their outputs to the variable load conditions on the grid. Plus, they mentioned that the details of the grid and the sources which are feeding it are the main parameters to determine the percentage of the power of the required storage [20].

Kawachi *et al*. (2010) discussed the importance of energy storage systems (ESSs) to control the power fluctuation of the renewable energy sources output; they studied the characteristic of the heat pumps power consumption in order to reduce the necessary capacity of ESSs for microgrid applications [21].

Teng *et al*. (2019) mentioned that the low flexibility of regulation capability of power grid after high proportion renewable energy connected to grid could be solved through energy storage. They studied electricity heat hydrogen multi-energy storage system (EHH-MESS), and they concluded that this type of storage has better economy compared with battery energy storage system and pumped storage power station, plus it could maximize new energy acceptance [22].

Knap *et al*. (2016) demonstrated that the energy storage system (ESS) could provide the response analogous to that provided by the conventional power plants (CPPs), and they presented the methodology of sizing the ESS in terms of required power and energy [23].

Nassereddine *et al*. (2016) covered the financial and environmental benefits of investing in a small-scale PV solar system with energy storage positioned at the load comparing with the infrastructure cost and electric loss in case of transportation of generated electric power from PV solar power plants [24].

Zsiborács *et al*. (2021) used real photovoltaic data from Hungary and Belgium to investigate how the accurate PV power generation forecast affect the level of utilization of energy storage system, and they mentioned that an energy storage system always has to be selected for a particular purpose, so the energy storage must be selected for each project and it is impossible to choose the best one in general [25].

Eltawil *et al*. (2010) discussed the challenges to increase system flexibility, taking into consideration the increase in demand variability created by intermittent sources like PV, traditional electric power systems are designed in large part to utilize large baseload power plants, with finite ability to rapidly ramp output or reduce output below a certain level [26].

Zsiborács *et al*. (2020) mentioned that by 2030, half of the electricity production will be from renewable energy sources, such as wind or solar energy. To enhance such robust growth, the EU policies and national laws related to the electricity market must introduce new instruments, such as energy storage devices, they conclude that the accuracy of PV power and energy forecasting has improved with the usage of the most recent (intraday) forecast method. The best forecast reduced the MW size of regulation compared to the day-ahead data [27].

Dyaka *et al*. (2018) mentioned that Jordan imports 97% of its energy and fuel requirements, nearly 20% of the country’s Gross Domestic Product, so this situation forced the government to reconsider its energy consumption policies. They studied the effect of integrating large-scale renewable energy on the stabile behavior of the Jordanian transmission grid based on the 2017 scenario, using Digital Simulation and Electrical Network Calculation (DigSILENT) to analysis; they concluded that when the system reaches the peak load, the grid will be stable, but the system will face unstable situations when the system reaches low load due to loss of wind [28].

Gyalai-Korpos *et al*. (2019) presented a user-oriented and transparent modeling concept of the European calculator, a tool for delineating emission and sustainable transformation pathways at European and member state levels, and they investigated how new technologies of energy storage can help the stability of the European electricity system with increasing renewables penetration, demand-side measures, and decarbonization paths. Finally, they concluded that the electrical systems in the future would need to increase their flexibility in order to overcome the variable renewable energy production on the supply side and shifting patterns of electricity consumption on the demand side [29].

Alrwashdeh (2018) studied the production of the PV racks with Appling different canopy form factors. It is found from the result of the simulation that. The maximum energy output for the PV racks was for the PV racks with the flat canopy form factor, with an energy production of 40467 kWh/year. In contrast, the minimum output of energy was 39000 kWh/year for the PV racks with buffer and ridge canopy form factors [30].

Dyak *et al*. (2017) investigated the technical and economic influences of integrating large-scale renewable energy projects of wind and PV systems to the transmission grid in Jordan up to the year 2025. They found that until 2018 Jordan’s transmission grid will face minor overloads, while most transmission lines will be overloaded by 2020 [31].

Hosenuzzaman *et al*. (2015) mentioned the importance of using a clean and sustainable energy source, such as solar energy, which is CO2-emission-free energy and is inexhaustible energy. It was found that PV is an easy way to capture solar energy where PV-based power generation has also rapidly increased [32].

Al-Ghussain *et al*. (2020) considered Al-Tafilah in Jordan as a case study. A tri-hybrid system of wind, solar, and hydropower was integrated with an energy storage system (ESS) and optimized to maximize the match between the energy demand and production profiles, and they found that without an ESS, the hybrid system could only reach up to 71.5% RES fraction. However, the analysis showed that the optimal system in Al-Tafilah comprising a 28 MW wind turbine, 75.4 MW PV, 1 MW hydropower, and a 259 MWh energy storage facility could increase the RES fraction to 99% [33].

Kebede *et al*. (2018) studied how an emission-free hybrid power system of solar, wind, and fuel cell power source unit for a given rural village in Ethiopia called Nifasso could meet the electricity demand in a sustainable manner, using HOMER in this techno-economic feasibility study. They conclude that community electric demand can be satisfied by a hybrid system power source containing 110 kW PV, one PGE 20/25 wind turbine, a 40 kW converter, 120 Surrette S6CS25P batteries, a 5 kW fuel cell, a 25 kW electrolyzer, and a 15 kg hydrogen tank, so hybrid PV-wind-fuel cell power system can be considered as a good choice in this regard [34].

Al-Ghussain *et al*. (2018) studied many configurations of Photovoltaic, Hydrogen Fuel Cell (HFC), and Pumped Hydro Storage (PHS), where Middle East Technical University Northern Cyprus Campus (METU NCC) is the case study. They found that the integration of the HFC and PHS system with the PV system increases the RES fraction and the demand-supply fraction from 36.2% to 45.4% and from 23.9% to 35.1%, respectively. The proposed system contains 2.57 MW PV, 1.16 MWh HFC and 4.14 MWh PHS [35].

Al-Ghussain *et al*. (2019) investigated three scenarios to find the optimal sizes of renewable energy systems (RES):1) with pumped hydro storage (PHS), 2) with batteries, and 3) without energy storage system (ESS). The results show that the PV-wind hybrid system of 8 MW wind and 4.2 MW PV with 89.5 MWh PHS has the highest RES fraction (FRES) of 88.0%, and the highest demand-supply fraction as 42.6%. Moreover, the type and the capacity of both the RES and the ESS affected the economic and technical parameters of RESs [36].

Li *et al*. (2020) mentioned that the flexibility of power systems to manage variability and uncertainties is becoming increasingly important as the penetration of variable renewable energy continues to rise [37].

Abu-Rumman *et al*. (2020) mentioned that Jordan's demand for energy is growing at a rate of 3% annually. In response, the government set a target of obtaining 10% of its energy needs from renewable energy resources by increasing electricity generation share from the present 1.13 GW–1.8 GW by 2020. Jordan has the means to become a regional energy and technology hub in the MENA region due to its political and economic stability [38].

Alrwashdeh *et al*. (2018) mentioned that the solar energy potential in Jordan is huge because it lies within the solar belt of the world with average solar radiation between 4 and 8 KWh/m2, which implies a potential of 1400-2300 GWh per year annually. This availability of solar radiation should be utilized because electricity demand in Jordan plays a considerable role in the high amount of energy consumption to cover the needs of heating, cooling, lighting, etc. [39].

Ogunniyi *et al*. (2017) Compared battery energy storage system (BESS) with other energy storage systems, they found that BESS has more tenacity to participate in a faster electric future due to their simple-efficient way of storing energy and their less complexity in interfacing with the common renewable energy sources in the recent time especially solar and wind energy [40].

Nadeem *et al*. (2019) mentioned that the energy storage system is becoming more widespread, and more innovative technologies saw the light in current research, which focuses on two main points: finding new chemical or topologies that can store more energy per unit volume and driving the construction costs down so that same energy can be stored for less cost [41].

Rugolo *et al*. (2012) presented a framework to determine the required storage power as a function of time for any power production profile, supply profile, and targeted system efficiency, given the loss characteristics of the storage system, with sufficient electricity storage capacity, any power production profile may be mapped onto any desired supply profile [42].

Goebel *et al*. (2017) investigated residential energy storage system which containing Lithium-ion (Li-Ion) batteries combined with solar photovoltaic (PV) panels, and they concluded that the residential battery storage system need for further battery cost reductions to achieve profitability under all considered circumstances, e.g., household sizes and locations [43].

Li *et al*. (2014) compared between hybrid solar-wind power system with a solar power system and a wind power system. Results show that the proposed hybrid scheme is feasible to reduce the ESS capacity by taking advantage of the complementary nature of solar vs. wind generation. They mentioned that to reduce the capital investment for the storage devices, it is important to estimate reasonable storage capacities. So the capacity of the ESS should be reduced to maximize the economic benefit that can be obtained from energy captured from the hybrid renewable sources [44].

Yu *et al*. (2013) mentioned that the charging and discharging of grid-tied Energy Storage Systems (ESS) distribution network could shift load from peak period or suppress the fluctuation of renewable energy. Power supply & storage capacity of distribution network with ESS quantify the ability of distribution network to shift load or adopt renewable energy generation [45].

In this work, optimal storage properties of PV solar storage systems in Jordan were determined to enhance grid penetration of PV systems efficiently and substantially. These properties including the grid flexibility factor, the corresponding size of the No-Dumped system (ND), and the solarizable load profile for each flexibility. Furthermore, and in order to characterize the storage system, the following parameters were estimated: energy capacity of the storage, power capacity of the storage, energy capacity/power capacity ratio (capacity ratio (CR)), PV system size limits. Finally, the relationships between these parameters would be investigated to determine their influence on the grid penetration of large photovoltaic power plants.

This work was achieved by selecting a 1MW PV project in Amman (south-facing and tilt angle equal 27˚). The National Electric Power Company (NEPCO) provided the hourly generation data, including hourly data for the demand, hourly generation data of the conventional sources, hourly generation data of total solar capacity, and hourly generation data of total wind capacity. MATLAB software was used to simulate algorithms developed by (Solomon 2014) to find the Energy capacity, Power capacity, and other storage characteristics.

2. Methodology

In this section, The hourly generation data provided by both the National Jordanian Electric Power Company and the I MWp project over twelve months (21/11/2016 to 21/11/2017) are presented and discussed. The methodology used in this work follows the following steps:

1. The hypothesis to be tested states that no PV energy losses are permitted other than those due to storage inefficiency.
2. The mathematical value of the grid flexibility from the obtained data was calculated.
3. A suitable value of the grid flexibility according to the profile of the generating units, especially the Diesel engine units and the hourly generation data of the 1MWp PV project, was selected.
4. The hourly surplus PV energy from a given sized PV system was identified.
5. The NO-dump (ND) PV project size for each grid flexibility was identified.
6. Energy capacity, Power capacity, and other storage characteristics were simulated estimated Using MATLAB software after applying to Jordan as a case study.
7. The storage system size variation with surplus energy generated by the PV system was investigated using MATLAB software.

3. Theoretical Background

- Grid flexibility (*ff*) factor is defined as (Denholm and Margolis [1]):

$$ff = t_{max} - \frac{t_{min}}{t_{max}} \tag{2.1}$$

Where tmax and tmin are the annual maximum and minimum hourly output of the grid system, respectively.

The high flexibility factor of the grid, which means the ability of the grid to ramp rapidly up and down, plays an important role in the efficient inputting of PV-generated power.

- No-dump (ND) PV system.

ND system is defined as the largest PV system that could deliver all of its annual production to the grid without any need for spillage (A.A. Solomon, 2014 [9]).

- Storage properties
    1. Energy capacity is defined as how much energy may be stored (Deholm and Margolis, 2007 [2])
    2. Power capacity is defined in the hour for which PV generation takes its extreme value.
    3. Capacity ratio CR.is, the ratio: energy capacity/power capacity which called.
- Daily surplus energy: the sum of the amounts of hourly PV energy generated in excess of each hour's solarizable load over a 24-hour period
- Solarizable load indicates the part of the load that PV could cover (including storage if available). The variable part of the grid load for a particular grid flexibility (ff) was computed by subtracting a constant baseload value from the total hourly load.
- The real hourly baseload was found to differ thought the year, but it could approximate to the constant value given by (Solomon 2014 [9]):

$$[1 - ff] * t_{max} \tag{2.2}$$

The hourly share of variable part Isi is (Solomon 2014):

$$I_{si} = t_i - [1 - ff] * t_{max} \tag{2.3}$$

Where ti represent the hourly grid output at time i,

- Usefulness index (UI) is the ratio of energy delivered by storage in a year to the energy capacity of storage

4. Results and Discussion

4.1. Overview of Grid Flexibility Results

The grid flexibility in Jordan was calculated to be nearly 0.65. However, it could be higher than 0.65 if the share of Diesel engines in annual production increased and if the Diesel engine units had a more flexible operation strategy, such as rescheduling their use to better coincide with solar availability.

In the following results, the flexibility was assumed to be 0.7 as being characterized by a modest increase, and also the storage properties would be studied at *ff*=0.8 and 1.

4.2. Overview of ND Results

As a first step, the results that correspond to an ideal grid (flexibility factor *ff* = 1) are presented using the hourly output of the 1 MWp PV Project in Amman. The ND size was found to be 1.6 GW, and the maximum amount of PV energy that could be fed into the grid without dumping is 16.4% of the annual demand. If the PV size increases to 2 ND and 3 ND, its penetration in the grid will be increased to 31% and 38%, respectively.

Figures **1** and **2** show the daily demand curve and the daily output of an ND PV (*ff*=1) system, respectively. Both curves are normalized to the maximum annual daily demand. It may be noticed that the demand is greater in the winter and summer seasons comparing to it during spring and autumn. On the other hand, the maximum PV output is from March to September, while the PV output is lower in winter.

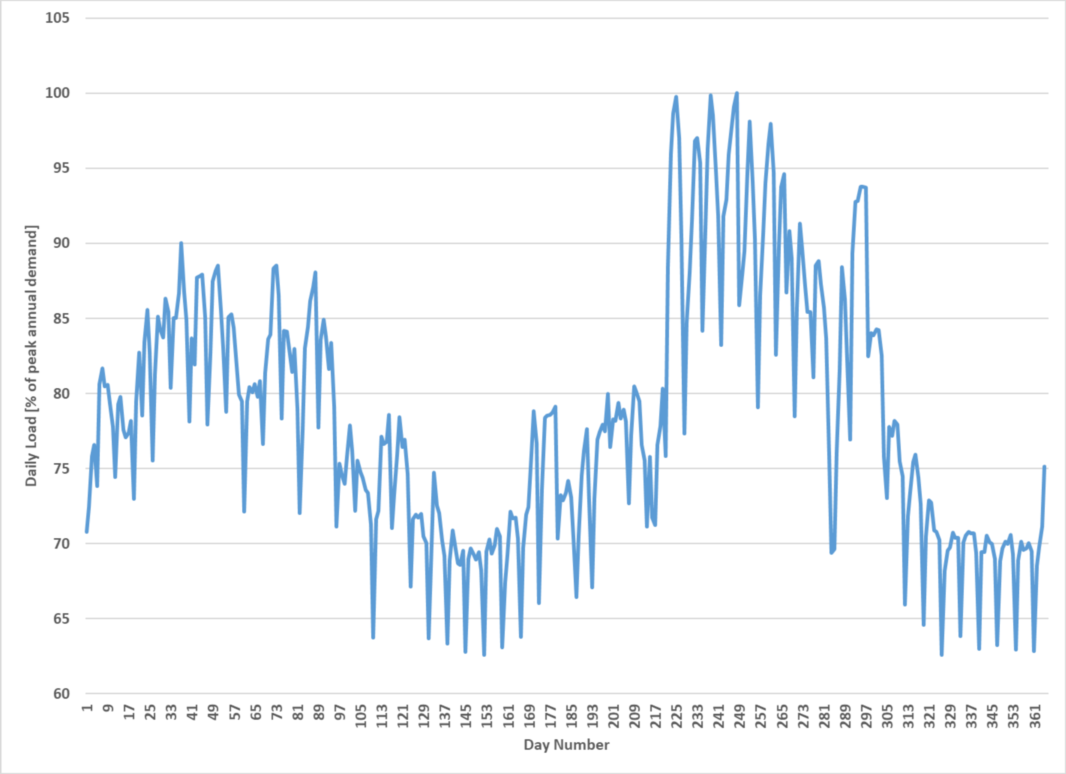

Figure 1: Daily demand curve.

The above results correspond to an ideal grid with *ff*=1, while in the real grid, which has limited flexibility, it was found that the ND size at flexibilities 0.8 and 0.7 are 998.4MW, 566.3 MW, respectively, and the largest amount of PV energy that could be injected to the grid without dumping for *ff*=0.8 and 0.7 are 9.7% and 5.5%, respectively.

4.3. Storage Requirement Results

After applying the algorithm using the hourly data from the National Jordanian electric power company, appropriate properties of the storage system are obtained. In the following sections, these properties are shown and will be discussed how these properties vary with many factors such as PV system size and grid flexibility.

4.3.1. Energy Capacity Results

Figure **3** illustrates the daily surplus energy generated by PV systems of sizes 3ND, 5ND, and 7ND at grid flexibility ff=0.7. From this figure, it can be noticed that most surplus energy comes in spring and summer times.

The surplus increases once more in winter, but it does not reach the spring maximum. However, there is a poor match between solar availability during the day and early evening peak loads in winter. This is why storage is required once more. However, because solar generation is lower in the winter, the necessary energy capacity of storage is smaller than in the spring.

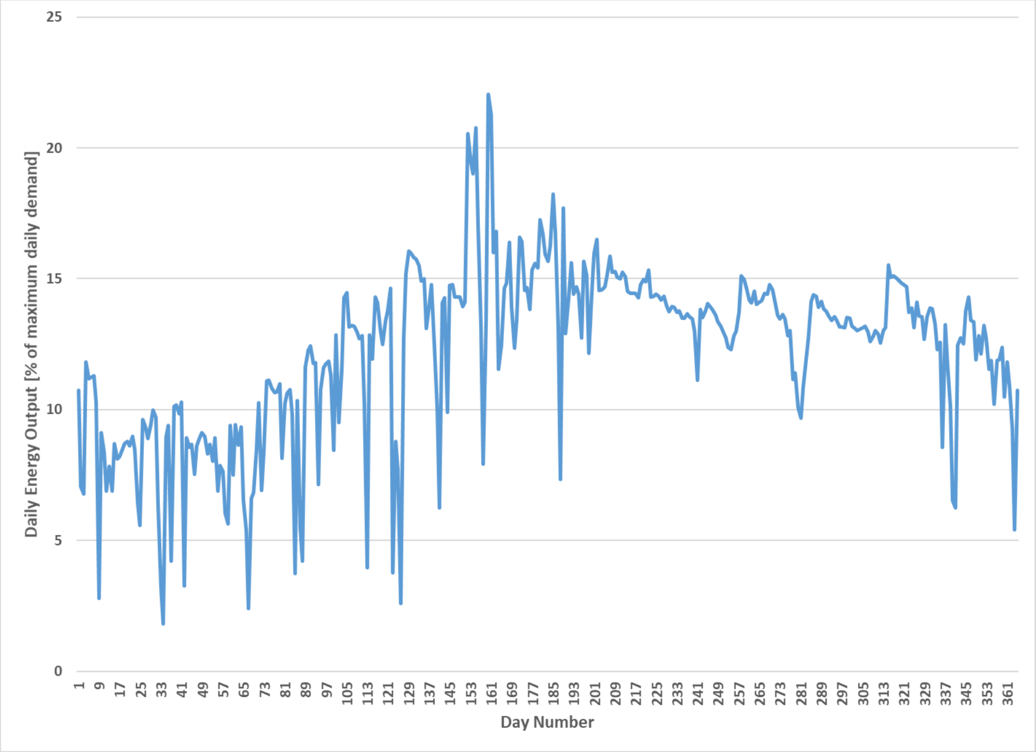

Figure 2: Daily output from a ND PV (*ff*=1).

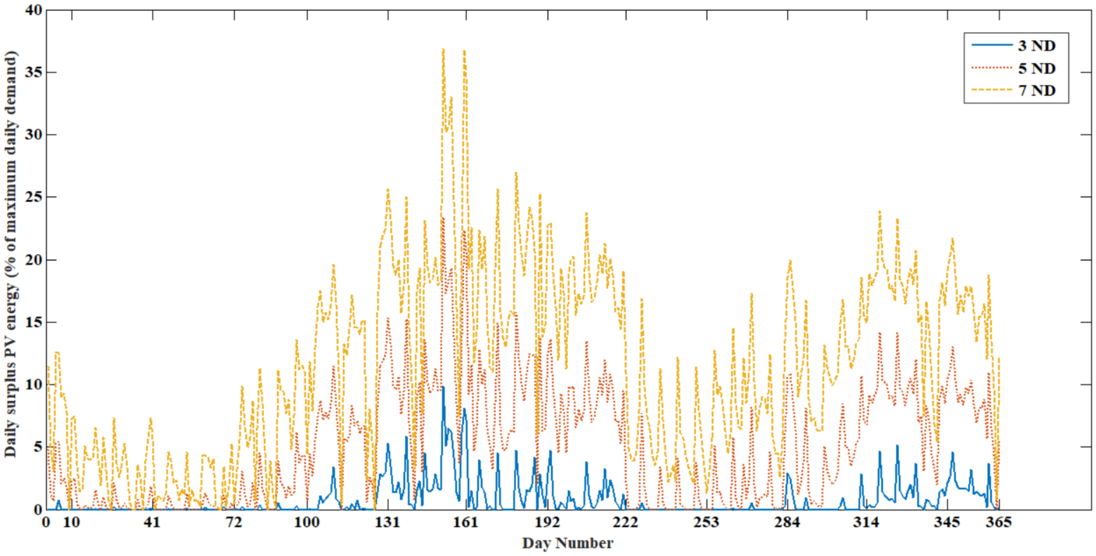

Figure 3: Daily surplus energy at grid flexibility ff=0.7.

Figure **4** shows the required daily storage energy capacity for PV systems of sizes 3, 5, and 7 ND, for grid flexibility=0.7. The annual required energy capacities for PV system sizes 3, 5, and 7 ND are approximately 6.7, 15.8, and 50 GWh, respectively.

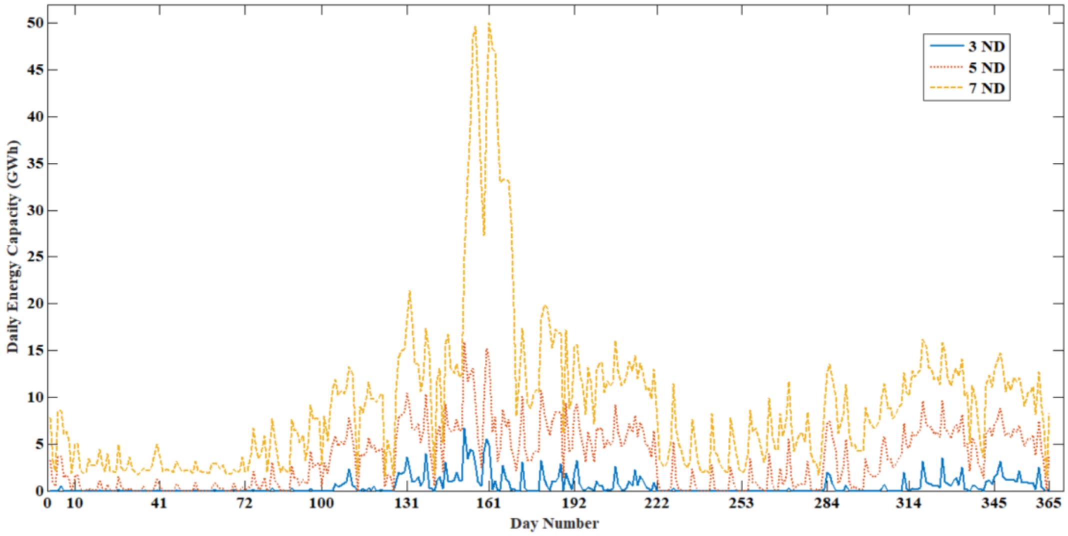

Figure 4: Daily storage energy capacity for PV systems of sizes 3, 5, 7 ND.

Figure **5** shows the daily surplus PV energy in relation to the daily solarizable load. It can be seen that for PV sizes below 5 ND, the daily surplus PV energy is almost always lower than the daily total solarizable load. Under these conditions, the energy stored during the day can be consumed the next night entirely, allowing the energy capacity to be calculated using the maximum total surplus PV energy.

However, when PV System size increase over 5 ND, the ratio of surplus energy to the matching daily solarizable load exceeds unity. In such a case, the energy stored during the day will not discharge completely during the next night.

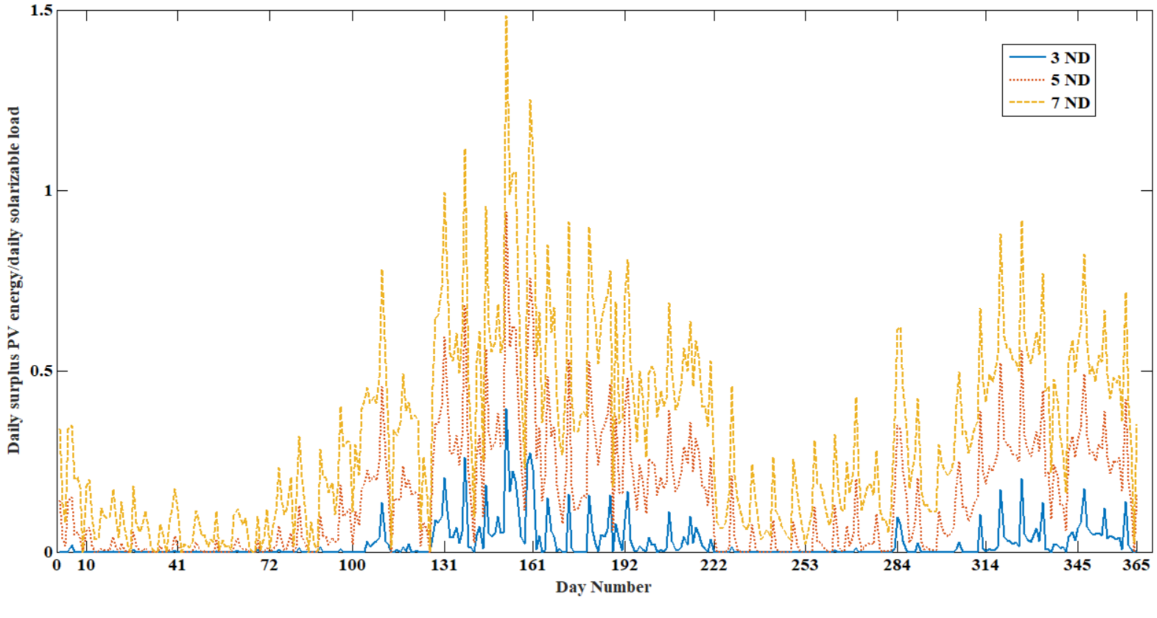

Figure 5: Daily surplus PV energy related to the daily solarizable load.

Figure **6** shows the relation between energy capacity and the PV system size every year for all grid flexibilities. As it may be seen, the required energy capacity increases linearly with PV system size until it reaches 5 ND, beyond which the required energy capacity increases at a higher rate. So, it can be concluded that the energy capacity varies according to PV system size, keeping the assumption that the energy losses are limited to those due to storage inefficiency.

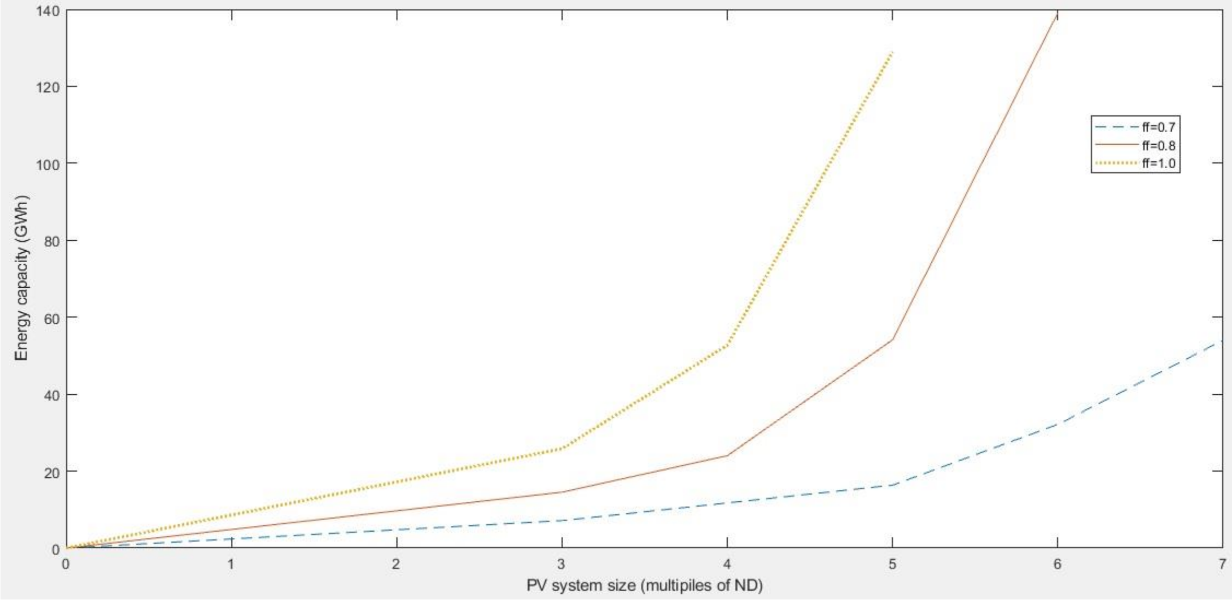

Figure 6: Relation between energy capacity and the PV system size.

4.3.2. Power Capacity Results

Figure **7** shows the daily power capacity. It may be noticed that the maximum power capacity occurs in the springtime.

Considering the total PV energy losses equal to 10% of the total PV generation, the power capacity at *ff*=0.7 for PV size 3ND, 5ND, and 7N D are 1GW, 2GW, and 3GW, respectively.

So far, the power capacity was defined by the charging requirement for PV system size, but actually, it indicates the rate of charge and discharge. The power capacity is specified by the maximum of the hourly charging or discharging requirement. The upper limit for discharging requirement of the storage is the planned peak demand for the developing grid system during the year, which is in Jordan during the period under consideration equal to 3.3 GW.

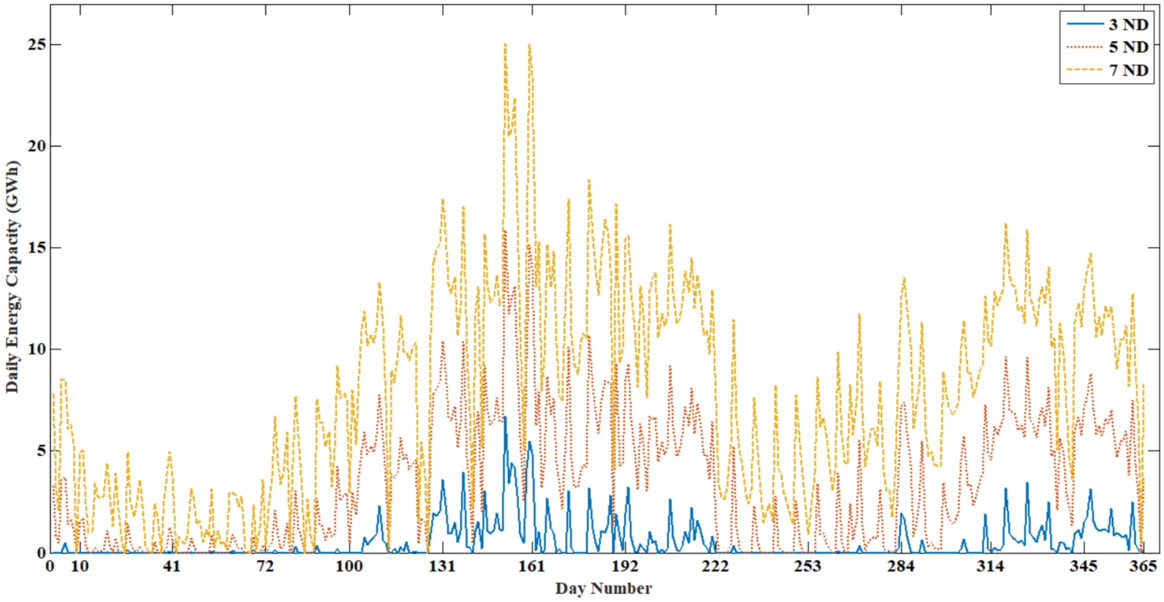

Figure 7: Daily power capacity.

4.3.3. Capacity Ratio CR Results

The previous sections studied the relations between energy capacity and power capacity with PV system size independently. In this section, their interdependence will be investigated.

Figures **8** and **9** show the relation between capacity ratio and PV system size at ff=0.7 and ff=1. It could be noticed from the figures that there exist three regions: in the first one, there is an initial increase in CR from size 1 ND, where no storage is needed, followed by the second region with little increase (almost constant) in approximate range 5 h for 2-4 ND systems. This is because the required power capacity and energy capacity show almost linear increases with PV system size. In the third region after 5ND, there is a sharp increase in PV system size. This steep increase in CR is because of the sharply increasing energy capacity combined with linear rising power capacity as PV system increase.

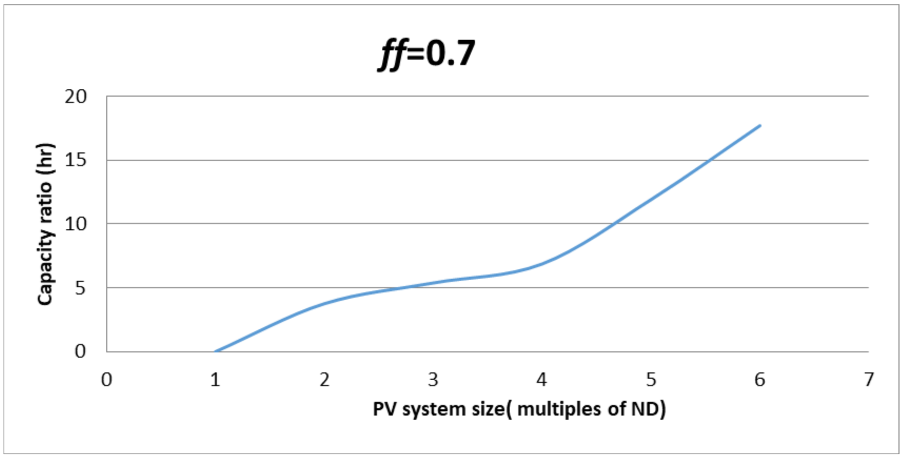

Figure 8: Relation between capacity ratio and PV system size at *ff* =0.7.

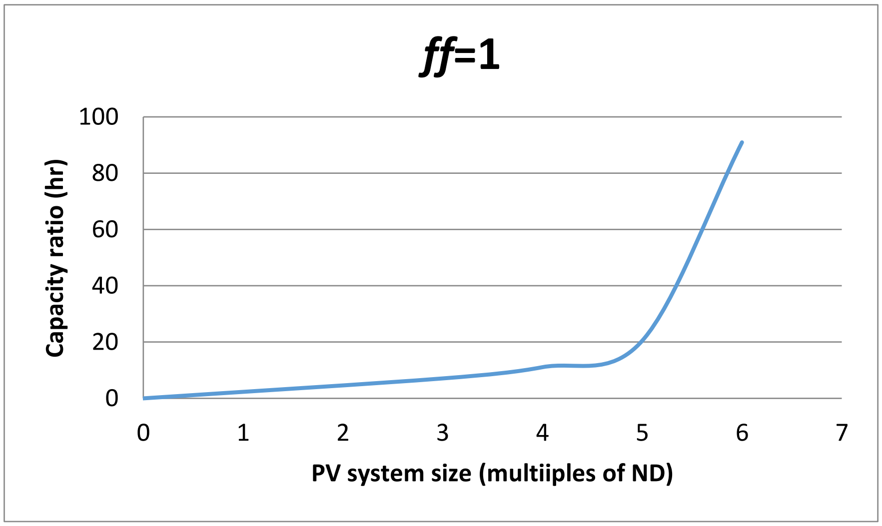

Figure 9: Relation between capacity ratio and PV system size at ff=1.

4.4. Indicators of Selecting a Properly Sized Storage

As mentioned earlier, it is hard to realize high grid penetration of PV energy without appropriate storage involved. This section illustrates how to determine a storage size that can enable a large PV system to achieve high PV grid penetration without a need to dump any generated PV power or acquiring the expenditure of oversized storage that would rarely be used.

4.4.1. A Usefulness Index, UI and Peak EC

Figure **9** shows the relationship between Usefulness Index (UI) and the Energy capacity at flexibility =0.7. As it can be noticed, initially, UI increases with increasing Energy capacity to a maximum value "Peak EC," beyond which it starts to decrease. This maximum value of EC occurs at flexibilities= 0.7 at energy capacity =16 GWh. In the same manner, it could be found that the "Peak EC" at flexibilities=0.8, 1 occur at energy capacity =24, 52 GWh, respectively.

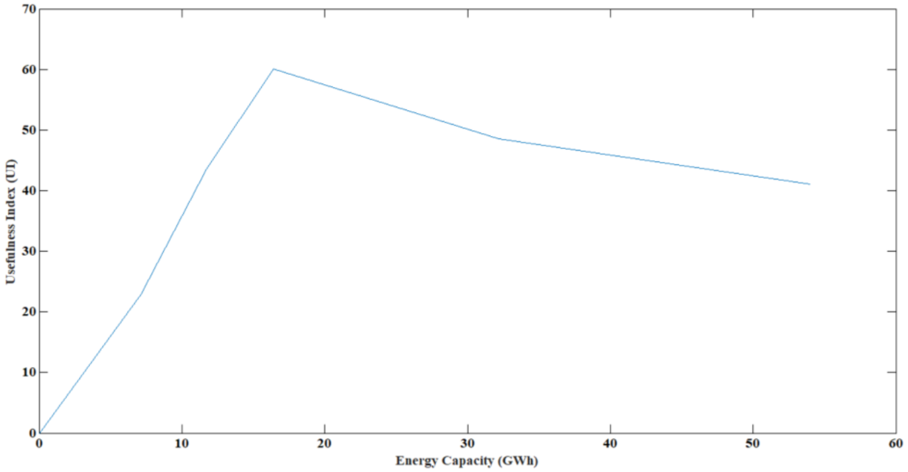

Figure 9: Relation of Usefulness Index (UI) and Energy Capacity (EC) of storage at *ff*=0.7.

Figure **10** illustrates how the annual energy delivered from storage (% of annual demand) depends on the Energy capacity for flexibilities 0.7. In the figure, it can be noticed that the annual delivered stored energy increases with energy capacity. Also, it can be noticed from the figures that there is a point at which a sudden change in slope occurs that is because, for small PV System size, there will be many days during which storage is not necessary as all the PV energy enters the grid directly. In such a case, the storage is under-used as the PV system size increase with the energy capacity. When the PV surplus production is more than the grid demand, some of the surpluses remain in the storage, and the energy capacity increases to a value larger than necessary. This point appears as a sudden change in the figure's slope, which happened at the same values of Peak energy capacity as in the figure.

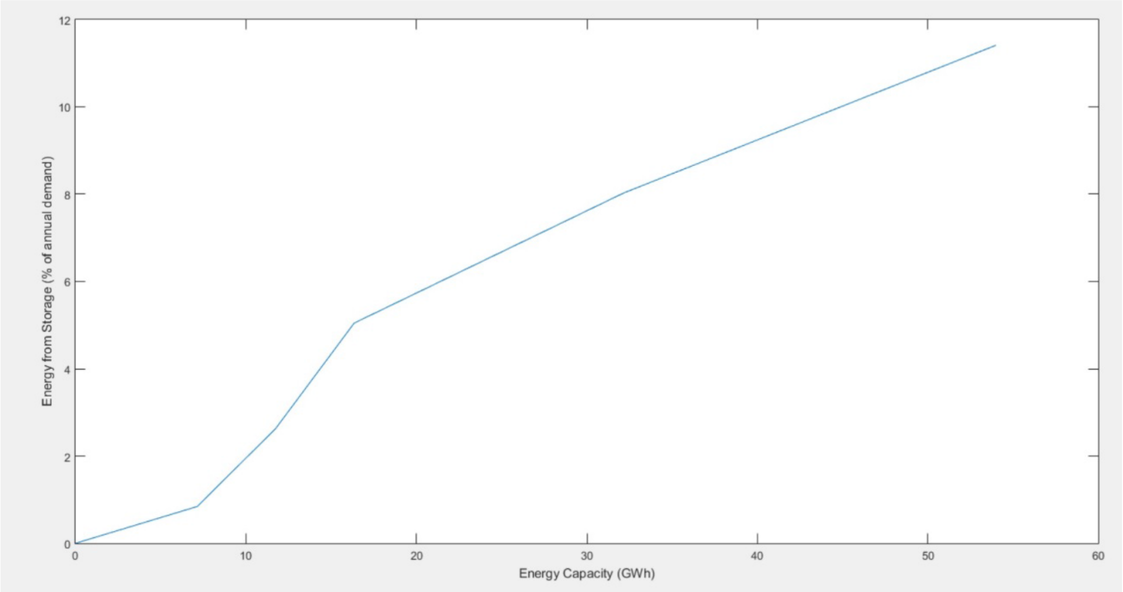

Figure 10: Dependence on Energy Capacity (EC) of the annual energy delivered to the grid from storage at *ff* =0.7.

4.4.2. High PV Grid Penetration

The ultimate target of using storage is to increase the penetration of PV into the grid. The term penetration represents the percentage of the total demand supplied by the direct Variable Renewable Energy (VRE) energy plus the stored one [16].

Figure **11** shows the relation between PV Grid penetration and the energy capacity at flexibilities 0.7. As shown in the figure, initially, the penetration increases with increasing PV system size almost linearly. However, at a specific point, a large increase in the energy capacity of the storage (along with a parallel increase in PV system size) reaches relatively minor growth in the annual grid penetration.

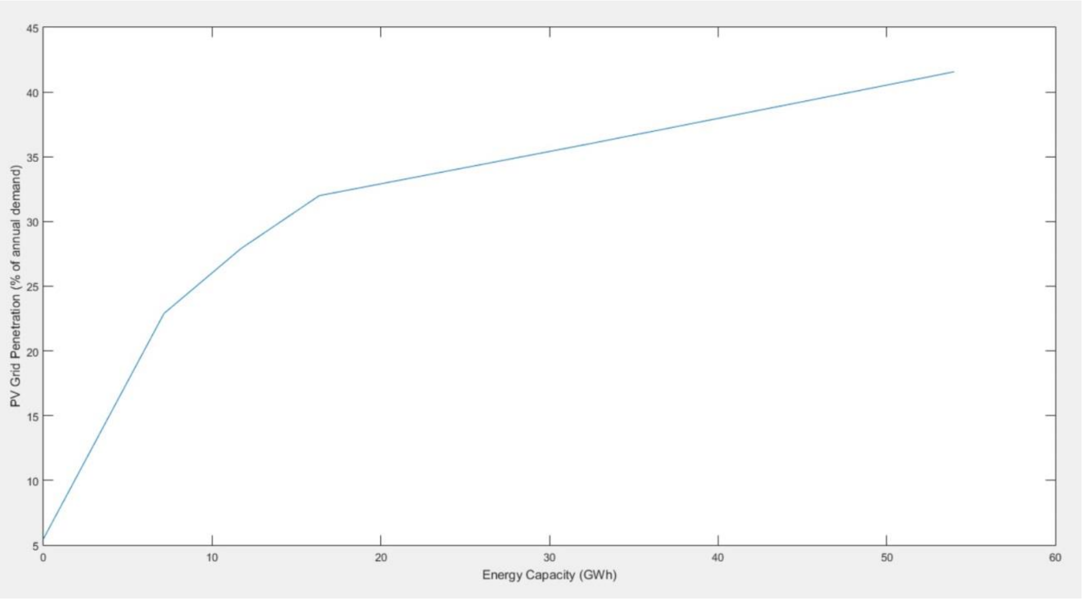

Figure 11: Dependence of PV penetration on the energy capacity required (*ff*=0.7).

Similarly, it can be noticed from the previous figures that penetration significantly increases with energy capacity, which occurs at the maximum Usefulness Index, and these EC values are referred as the "Peak EC".

Then it may be stated that for each given grid flexibility, there is a matched combination of PV system size and storage size that maximizes the storage's Usefulness index and generates a large grid penetration while at the same time avoiding unnecessarily large storage so resulting in the least storage cost.

4.6. A summary of Selecting the Suitably Sized Storage

Table **1** surmises the previous results for each grid flexibility. It is to be noted that these values are approximate ones. It can be noticed that all the storage properties increase with *ff,* which indicates that if in the future grid more PV share is required, it is essential to raise grid flexibility.

Table 1: Approximate values of Peak energy capacity, peak power capacity, and the achievable penetration for various grid flexibilities.

Grid Flexibility *ff*	**Penetration (% of Annual Demand)**	**PV System Size (GWp)**	**Energy Capacity (GWh)**	**Power Capacity (GW)**
0.7	34%	2.8	16.5	2.4
0.8	42%	3.9	24	3
1(ideal case)	68%	6.4	52.7	4.7

5. Current Storage Need in Jordan

As found earlier, the No-dump PV system (ND) at *ff*=0.7 was equal to 566.3 MW, and the current solar capacity in Jordan was equal to 1100 MW which is less than triple ND (3ND) (according to the National Electric Power Company's Annual report 2019). Consequently, there is no need for storage in the current stage. According to Jordan's First Biennial Update Report to the United Nations Framework Convention on Climate Change (UNFCCC) 2017, the expected share of solar energy by 2021 will equal to 1500MW. This capacity plus unexpected private PV projects form triple ND (3ND), so the need for storage in Jordan will be raised in the near future.

6. Conclusion

The following may be concluded from this work

1- The no-dump (ND) system size at *ff*=0.7 was found equal to 566.3 MW, and the largest amount of PV power that could be injected into the grid (without storage) is 5.5% of the annual demand.

2- The PV grid penetration increases with grid flexibility.

3- The energy capacity (EC) increases power capacity (PC)

4- At grid flexibilities 0.7,0.8 and 1, a PV grid penetration increase to 34%, 42%, and 68%, respectively, of annual requirements with installing storage; and actually, it could be increased the installed PV capacity to 2.8, 3.9, and 6.4 GWp for flexibilities 0.7, 0.8 and 1, respectively.

5. The need for storage in Jordan will be raised in the near future.

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