Jordan Journal of Energy
Volume 2, Number 1, 2024

ISSN (Online): 2790-7678
ISSN (Print): 2790-766X

Jordan Journal of Energy (JJE)
Journal Homepage: http://dsr.mutah.edu.jo/index.php/jje
JEE an official peer review journal of Mutah University,

Energy Storage Solutions to De-Carbonize the Electric Supply in Jordan

Abdulraheem A. A. Aljaradat
Arab Potash Company, Jordan,
Email: Abedalraheem.j@arabpotash.com

Received 21st, Jan 2024; Accepted 14th, August 2024

ABSTRACT. *This paper aims to estimate the size of Energy Storage Systems (ESS) required de-carbonizing the electrical network in Jordan. Load profile in addition to the PV (Photovoltaic) and Wind energy profiles were studied and used as input data to the simulation model. Different cases of RE (renewable Energy) penetration levels as a percentage of load demand were considered and entered to the simulation model as well. Other factors, such as allowed over-generation and ESS efficiency also provided and calculations carried out accordingly. In addition to the technical consideration, an economic analysis approach added to the study. Results show that staying with the current level of RE penetrations, i.e. at PV 11% and W 9% (RE level 20% of load demand) and 5% curtailment, no need to install ESS to absorb the RE intermittency and variability. As RE penetration level increases, the need for ESS becomes necessary, i.e. to reach 100% RE penetration and de-carbonize the electrical network accordingly, an ESS of 138,900.00MWH/ 7,386.57MW PHES would be required at PV 65% and Wind 35% penetration level and 25% curtailment with initial CAPEX investment of JOD 15,367,314,444.10. Economic feasibility study shows that with the current RE energy prices and ESS CAPEX, reaching the 100% RE penetration level would not be the optimum solution as there will be a negative cost impact, unless these prices reduced to a certain level making the solution feasible.*

Keywords: Energy Storage Systems, Renewable Energy, Photovoltaic, Wind Energy, Load Demand Profile, De-carbonization

1. Introduction. In Jordan as in other countries of the world, electrical energy is the main driver for industry and national economy. The energy sector faces many difficulties and challenges, mainly the lack of resources, i.e. Oil and Natural Gas, which are imported from neighbors and foreign countries and consequently increasing the public debit. Due to that, Jordan Governments had to look seriously for promising and practical solutions to reduce the energy and electricity invoice.

Jordan is rich of renewable energy resources, i.e. wind and sun radiation. This encouraged Government to start RE projects. As of 2022, the total share of renewable is around 20% of the total demand, according to NEPCO (National Electric Power Company) annual reports [1-2].

While renewable energy penetration is increasing and since the nature of this energy is intermittent and unpredictable, which causes frequency fluctuating, voltage issues, congestion issues and apparent need to upgrade the grid capacity to cope with the increasing peaks in the grid [3], the need for Energy Storage becomes necessary to utilize this energy in most effective way. Energy Storage System can absorb the energy fluctuation from renewable sources allowing for more renewable penetration and more carbon reduction. “Energy storage is a clear choice for absorbing the variability of renewable energy sources” [4]. Knowing that Energy storage is the choice to absorb the variability of renewable energy sources, it leads to the question of “What is the suitable type and size of Energy Storage System need to be used in order to achieve the most technically and commercially feasible solution?” In addition to that, identifying the renewable Energy penetration levels allows decision makers knowing the investment size in this field while taking the lead for the zero carbon emissions.

Dr. Suhil Kiwan and Elyasa Al-Gharibeh have suggested a 90 GWh storage system (43 CSP plants, 250 MW each, 8h storage) to solve the dispatch-ability issue when they proposed a 100% renewable solution for the Jordan network among other scenarios of mixed energies [4]. Internationally, “Results suggest that the UK could need a storage capacity of approximately 43 TWh to decarbonize its electricity supply. This figure considers a generation mix of 84% wind + 16% solar PV, a roundtrip storage efficiency of 70%, and 15% of curtailment. Based on current costs of bulk energy storage technologies, this storage capacity translates into an investment of about 165.3 billion £ or approximately 7% of the country’s GDP [3].

This paper aims to suggest ESS that can absorb the renewable energy sources’ variability and intermittency starting from low RE penetration until reaching the 100% (of demand) penetration, i.e. zero carbon emissions. In addition to the money value of 100% RE penetration, an energy wasting will take place by means of over-generation (curtailment) of the RE sources, this paper finds out the optimum value of the allowable over-generation. The proposed methodology is based on iterative process to find the required RE profile meeting a certain percentage of demand (up to 100%) and then subtracting it from the demand profile which results in positive and negative values that represent charging and discharging energies that can be used to calculate the storage capacities.

The organization of the rest of this paper are as a follow, in section 2 the profiles of the load demand, PV and Wind energy are presented and discussed, in section 3 the proposed method is briefly described, results and discussions are presented in section 4. Finally, the conclusion is presented in section 5.

2. National Grid Profile: Load, Wind and Solar Energy Profiles.

Load Profile

Figure-1 shows the daily/hourly Load Profile in the National Grid for one complete year, 2017, which also equals to the Generation supply; Grid is considered stable and hence supply matches the load. This one year profile will be used as input to the simulation model.

ISSN (Online): 2790-7678
ISSN (Print): 2790-766X

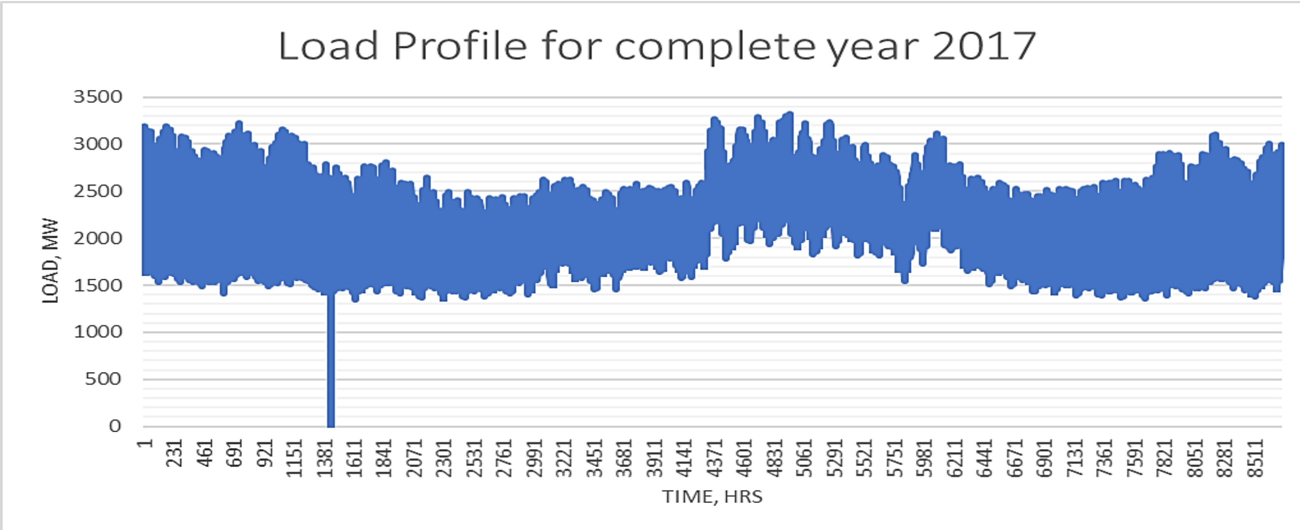

FIGURE 1: Grid Load Profile for complete year 2017

Renewable Supply Profiles

Wind Energy

Figures-2 shows the Wind Energy generation profile, for a complete year, 2017.

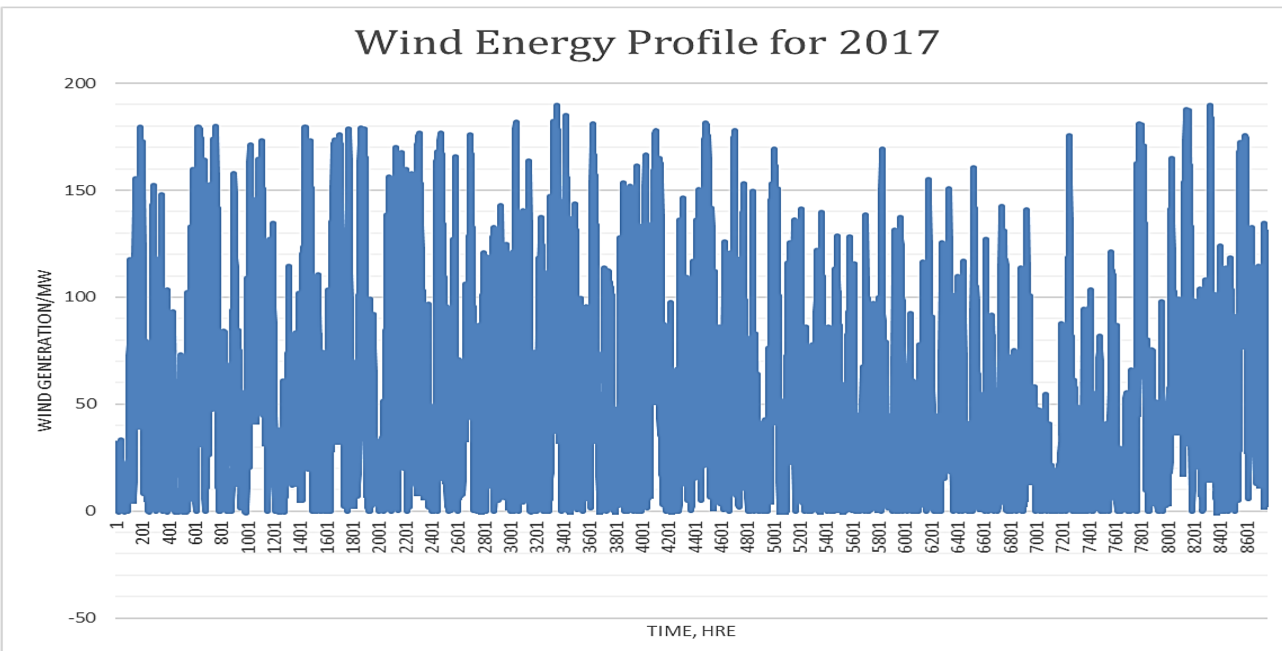

FIGURE 2: Wind Energy Generation Profile for complete year 2017

Further examination shows that wind energy follows a certain distribution curves, in the most cases it can be represented by Weibull distribution curve for each hour of the day, i.e. otherwise there will be 24 curves to represent the Wind energy profile.

Solar Energy

Figure-3 shows the solar Energy generation profile, for a complete year, 2017.

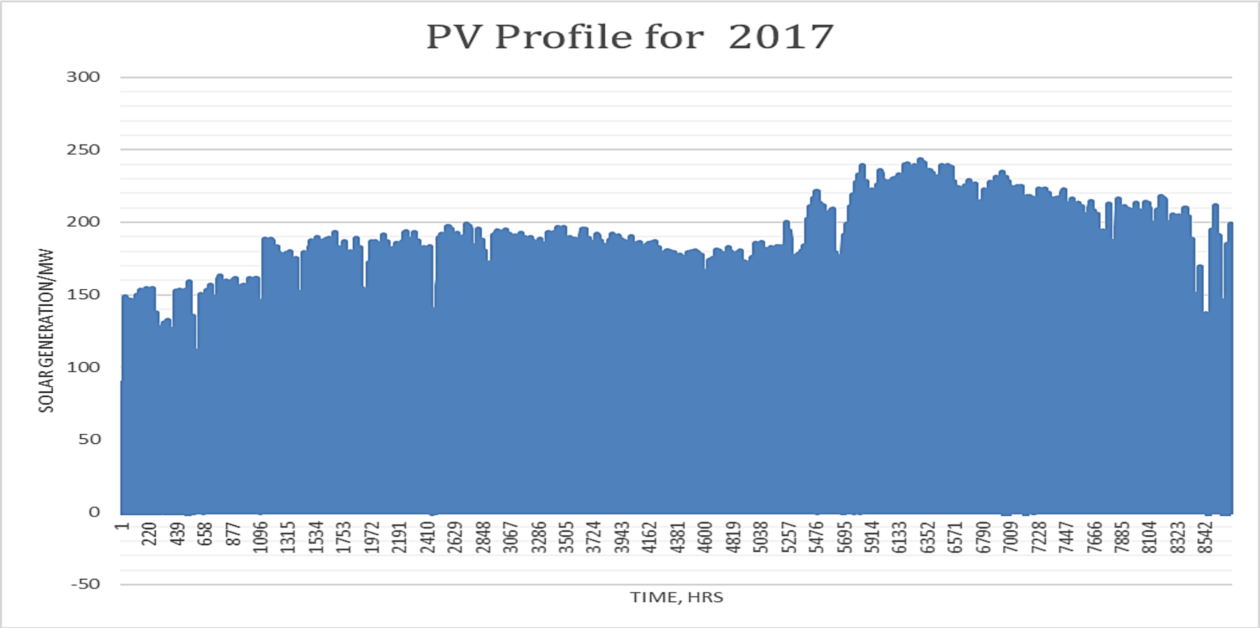

FIGURE 3: Solar Energy Generation Profile for complete year 2017

3. The Proposed Method.

The objective of this paper is to calculate the ESS size, i.e. Energy and Power ratings, which will be required to absorb the renewable energy intermittency at different levels of RE penetration as fraction of the load demand at the Jordanian Transmission network. Such studies can help decision makers envisaging the size of investments required to reduce the carbon emissions and planning for the RE projects execution in parallel with required ESS installations. As more RE penetration level is required, new PV and Wind energy projects need to be executed to replace the fossil fuel energy, at the same time ESS projects should be in place at the correct time to manage the RE intermittency.

The process of calculation is developed based on the proposed methodology in “Energy Storage Capacity vs. Renewable Penetration: A Study for the UK”. In this paper, authors have proposed a methodology to calculate the ESS by using an iterative process. The process starts by finding the required RE profile that need to meet a certain percentage of demand (up to 100%), and then subtracting it from the demand profile which results in positive and negative profiles, these values represent the charging and discharging energies, which will be used to calculate the storage capacities[4].

The following paragraphs briefly describe the main steps to calculate the storage size:

- Defining the PV and Wind penetration levels, i.e. for 50% RE penetration, PV and Wind could have a penetration level where the summation of both values equals to 50% of the required demand energy. Then setting the allowed curtailment energy and selecting the ESS efficiency according to the proposed technology, i.e. 80% for PHES and 90% for BESS.

ISSN (Online): 2790-7678
ISSN (Print): 2790-766X

- As the demand load profile is known, a net demand curve is obtained by subtracting a modified PV and Wind profiles from the demand profile. PV and Wind profiles are modified so they produce the required amount of energy related to the RE penetration level mentioned.
- Net demand curve is used to calculate total renewable produced energy, storage losses and amount of energy over generated.
- Conducting a check point to make sure that the obtained PV and Wind profiles meet the required energy as specified by RE penetration level.
- If the checkpoint is not met, another iteration is carried out until modified PV and Wind profiles meet the required energy as specified by RE penetration level.
- The amount of renewable generation required to achieve the specific penetration level defined has been calculated and the profile of net demand is now known.
- The obtained net demand profiles will be used to estimate the size of ESS. This is done by setting an ESS initial value, and then simulate the ESS charging/discharging cycles as we go by time stepping from first to last point in the demand and RE profiles. After completing the full length of the profiles, the total curtailed energy is calculated, if it is less than the specified value, then ESS size is found, otherwise a new iteration continues.

These steps are repeated at each set of PV and Wind energy penetration, allowed curtailment and ESS efficiency.

4. Results and Discussion: In this section, the results of the simulation are presented and discussed. At first, the selected ESS size at each RE penetration level represents the smallest ESS size that required achieving the allowed percentage of curtailment. This will examine the results from technical point of view. Then from commercially point of view, more calculations are carried out taking into consideration the different cost variables, Cost of Fossil Fuel, Wind energy, Solar energy, ESS CAPEX, etc…
Table-1, shows the results of 80% and 90% ESS Storage System Sizes, i.e. for different levels of RE penetration, 20%, 25%, 50% and 100%, and for different levels of allowed Curtailment, 0%, 5%, 10%, 15%, 20% and 25%.

An overall look to this table, the following statements can be concluded:

- As we allow for more curtailment, the required ESS size is reduced, it can reach 0 MWH in some cases.
- With zero allowed curtailment, always the ESS size is the highest value among other curtailment levels.
- As we go with almost balanced RE mixture (i.e. 50% to 50%), the ESS is reduced.
- As ESS efficiency increased, the ESS size is reduced, i.e. with same RE mixture and at same allowed curtailment, i.e. for 50% RE penetration, 5% Curtailment, the required ESS size at 25%

PV and 25% Wind is 3,280.00 MWH for 80% Efficiency system compared with 654 MWH of 90% Efficiency system.

- As RE penetration level increases the ESS size required increases, i.e. at 100% RE penetration (almost zero carbon emissions) and 5% curtailment, we need to install 708,900.00 MWH ESS (JOD 72,114,875,010.98) at 60%PV and 40% Wind, compared to Zero ESS at 20% RE penetration level.

TABLE 1: ESS SIZES AND CAPEX AT DIFFERENT RE PENETRATION LEVELS, DIFFERENT CURTAILMENTS AND TWO DIFFERENT SYSTEMS EFFICIENCIES.

ESS System, η =80%, i.e. PHS							ESS System, η =90%, i.e. BESS						
RE Mix	Curtailment Ω	PV%	W%	ESS Energy Size MWH	ESS Power Size MW	ESS CAPEX	RE Mix	Curtailment Ω	PV%	W%	ESS Energy Size MWH	ESS Power Size MW	ESS CAPEX
20%	0%	7%	13%	2,300	3,918	JOD 1,013,565,249.75	20%	0%	13%	7%	53	3,483	JOD 881,228,055.28
	5%	2 to 18%	18 to 2%	0.00	0.00	JOD 0.00		5%	0 to 20%	20 to 0%	0.00	0.00	JOD 0.00
	10%	0 to 19%	20% to 1%	0.00	0.00	JOD 0.00		10%	0 to 20%	20 to 0%	0.00	0.00	JOD 0.00
	15%	0 to 20%	20% to 0%	0.00	0.00	JOD 0.00		15%	0 to 20%	20 to 0%	0.00	0.00	JOD 0.00
	20%	0 to 20%	20% to 0%	0.00	0.00	JOD 0.00		20%	0 to 20%	20 to 0%	0.00	0.00	JOD 0.00
	25%	0 to 20%	20% to 0%	0.00	0.00	JOD 0.00		25%	0 to 20%	20 to 0%	0.00	0.00	JOD 0.00
25%	0%	14%	11%	4,664.00	3,917.83	JOD 1,249,965,249.75	25%	0%	9%	16%	734.00	3,482.51	JOD 1,017,428,055.28
	5%	5% to 20%	20% to 5%	0.00	0.00	JOD 0.00		5%	0% to 25%	25% to 0%	0.00	0.00	JOD 0.00
	10%	2% to 22%	23% to 3%	0.00	0.00	JOD 0.00		10%	0% to 25%	25% to 0%	0.00	0.00	JOD 0.00
	15%	0% to 23%	25% to 2%	0.00	0.00	JOD 0.00		15%	0% to 25%	25% to 0%	0.00	0.00	JOD 0.00
	20%	0% to 23%	25% to 2%	0.00	0.00	JOD 0.00		20%	0% to 25%	25% to 0%	0.00	0.00	JOD 0.00
	25%	0% to 24%	25% to 1%	0.00	0.00	JOD 0.00		25%	0% to 25%	25% to 0%	0.00	0.00	JOD 0.00
50%	0%	35%	15%	18,076.00	3,917.83	JOD 2,591,165,249.75	50%	0%	33%	17%	14,200.00	3,482.51	JOD 3,710,628,055.28
	5%	25%	25%	3,280.00	3,917.83	JOD 1,111,565,249.75		5%	25%	25%	654.00	3,482.51	JOD 1,001,428,055.28
	10%	23%	27%	772.00	3,917.83	JOD 860,765,249.75		10%	15% to 38%	35% to 22%	0.00	0.00	JOD 0.00
	15%	18% to 25%	25% to 32%	0.00	0.00	JOD 0.00		15%	13% to 33%	37% to 13%	0.00	0.00	JOD 0.00
	20%	15% to 28%	35% to 22%	0.00	0.00	JOD 0.00		20%	10% to 33%	40% to 17%	0.00	0.00	JOD 0.00
	25%	13% to 30%	37% to 20%	0.00	0.00	JOD 0.00		25%	8% to 35%	43% to 15%	0.00	0.00	JOD 0.00
75%	0%	70%	5%	51,110.00	4,432.36	JOD 5,997,471,205.48	75%	0%	65%	10%	41,800.00	4,003.81	JOD 9,360,953,188.73
	5%	50%	25%	18,180.00	4,347.29	JOD 2,687,458,265.89		5%	50%	25%	13,790.00	3,908.14	JOD 3,735,034,571.19
	10%	45%	30%	13,610.00	4,587.64	JOD 2,278,528,399.11		10%	40%	35%	10,460.00	4,276.25	JOD 3,161,062,169.75
	15%	40%	35%	10,760.00	4,848.13	JOD 2,045,626,535.01		15%	35%	40%	7,840.00	4,556.84	JOD 2,707,209,158.50
	20%	35%	40%	8,670.00	5,122.96	JOD 1,891,592,922.89		20%	35%	40%	5,880.00	4,822.83	JOD 2,381,708,582.73
	25%	35%	40%	7,110.00	5,380.94	JOD 1,787,187,630.28		25%	30%	45%	4,540.00	5,119.72	JOD 2,187,929,922.28
100%	0%	75%	25%	1,210,900.00	5,788.47	JOD 122,247,693,324.63	100%	0%	70%	30%	1,128,500.00	5,460.07	JOD 227,065,018,630.96
	5%	60%	40%	708,900.00	6,124.38	JOD 72,114,875,010.98		5%	60%	40%	632,700.00	5,856.19	JOD 128,004,047,891.29
	10%	50%	50%	302,900.00	6,398.93	JOD 31,569,785,361.83		10%	45%	55%	438,700.00	6,297.43	JOD 89,314,356,629.08
	15%	55%	45%	200,900.00	6,732.17	JOD 21,436,434,070.30		15%	40%	60%	368,000.00	6,696.23	JOD 75,274,057,815.40
	20%	60%	40%	173,700.00	7,061.39	JOD 18,782,277,097.73		20%	40%	60%	332,100.00	7,049.67	JOD 68,182,416,271.69
	25%	65%	35%	138,900.00	7,386.57	JOD 15,367,314,444.10		25%	35%	65%	315,100.00	7,450.39	JOD 64,882,596,987.78

ISSN (Online): 2790-7678
ISSN (Print): 2790-766X

TABLES-2 and 3 show the results for the most feasible solutions of 80% and 90% ESS Storage Systems, i.e. PHES and BESS respectively, at different levels of RE penetration, 20%, 25%, 50% and 100%, and for different levels of allowed Curtailment, 5% to 25% at 5% steps.

An overall look to these tables, the following statements can be concluded:

- The most feasible solution among all proposed mixtures and allowed curtailment, is to have 20% RE penetration level, with 5% allowed curtailment, 15% Solar percentage, 5% Wind percentage, in this case no need for ESS system, i.e. RE can be absorbed within the network easily, but with small amount of curtailment.

- As more curtailment is allowed, the ESS size is reduced, and many cases ESS can selected as Zero value.

- As we go for more RE penetration, the required ESS size is extremely increased, and solution becomes not feasible from commercial point of view.

- It is still feasible to have more RE penetration level and hence reduce more carbon, i.e. we can go up to RE 50% penetration level (23% PV, 27% Wind) and with 0 ESS Size, but with 20% curtailment, i.e. 20% of produced RE will be wasted.

- With 50% RE penetration (28% PV, 22% Wind), if ESS with 3,400.00MWH/3,917.83MW and JOD 1,123,565,249.75 CAPEX is selected with 5% allowed curtailment, then this combination would be more feasible than not having ESS system.

- For lower RE penetration, required ESS has power component higher than Energy component, i.e. ESS solution would be Flywheels; its Power rating higher than Energy rating.

- For higher RE penetration, required ESS has power component less than Energy component, i.e. ESS solution would be PHS or Battery Energy Storage; its Energy rating higher than Power rating, see Figure-2 to understand the relation between Energy and Power of different Storage techniques.

TABLE 2: Optimum ESS values at different energy types' cost for η=80% and 50 years lifetime

ESS System, η =80%, i.e. PHS, ESS Life time 50 years.													
RE Mix	Curtailment Ω	PV%	W%	ESS Energy Size MWH	ESS Power Size MW	ESS CAPEX JOD	Fossil Fuel MWH	Curtailed Energy MWH	Wind Energy MWH	Solar Energy MWH	Sold Energy MWH	ESS CAPEX Annuity	Annuity Cash In JOD
20%	0%	16%	4%	2,672.00	3,917.83	JOD 1,050,765,249.75	12,367,729	0	1,386,976.34	5,547,905.36	19,295,703	85,892,555	132,469,182
	5%	15%	5%	0.00	0.00	JOD 0.00	12,191,541	33,087	1,784,315.30	5,352,945.90	19,295,703	0	232,292,440
	10%	15%	5%	0.00	0.00	JOD 0.00	12,072,954	42,348	1,816,278.54	5,448,835.62	19,295,703	0	231,067,552
	15%	15%	5%	0.00	0.00	JOD 0.00	11,910,335	59,374	1,861,190.56	5,583,571.69	19,295,703	0	228,775,092
	20%	14%	6%	0.00	0.00	JOD 0.00	11,796,871	49,323	2,264,451.17	5,283,719.39	19,295,703	0	227,395,926
	25%	14%	6%	0.00	0.00	JOD 0.00	11,617,586	67,336	2,323,641.65	5,421,830.52	19,295,703	0	224,900,489
25%	0%	21%	4%	5,041.00	3,917.83	JOD 1,287,665,249.75	11,552,189	0	1,246,053.92	6,541,783.09	19,295,703	105,257,438	134,699,530
	5%	17%	8%	0.00	0.00	JOD 0.00	11,413,035.33	82,585.64	2,548,887.65	5,416,386.26	19,295,703	0.00	221,588,020
	10%	16%	9%	0.00	0.00	JOD 0.00	11,225,688.57	88,653.38	2,937,127.10	5,221,559.29	19,295,703	0.00	218,266,555
	15%	16%	9%	0.00	0.00	JOD 0.00	11,056,761.80	111,183.13	3,006,053.11	5,344,094.41	19,295,703	0.00	215,037,881
	20%	16%	9%	0.00	0.00	JOD 0.00	10,892,574.49	137,293.69	3,074,562.24	5,465,888.43	19,295,703	0.00	211,299,341
	25%	15%	10%	0.00	0.00	JOD 0.00	10,708,966.16	144,265.23	3,492,411.39	5,238,617.08	19,295,703	0.00	207,615,144
50%	0%	35%	15%	18,076.00	3,917.83	JOD 2,591,165,249.75	7,648,162	0	3,593,427.47	8,384,664.10	19,295,703	211,809,253	2,632,492
	5%	28%	22%	3,400.00	3,917.83	JOD 1,123,565,249.75	7,712,238.37	482,061.86	5,485,419.07	6,704,401.09	19,295,703	91,843,434.85	53,483,154
	10%	25%	25%	925.00	3,917.83	JOD 876,065,249.75	7,661,651.47	964,616.04	6,321,531.50	6,321,531.50	19,295,703	71,612,077.45	5,008,170
	15%	23%	27%	0.00	0.00	JOD 0.00	7,527,502.39	1,278,709.26	7,179,342.43	5,874,007.45	19,295,703	0.00	28,889,931
	20%	23%	27%	0.00	0.00	JOD 0.00	7,290,747.24	1,473,407.09	7,416,853.34	6,068,334.55	19,295,703	0.00	465,321
	25%	23%	27%	0.00	0.00	JOD 0.00	7,116,637.79	1,634,557.09	7,601,361.78	6,219,296.00	19,295,703	0.00	-23,020,033
75%	0%	70%	5%	51,110.00	4,432.36	JOD 5,997,471,205.48	3,932,122	0	1,122,523.82	15,715,333.53	19,295,703	490,250,438	-318,598,824
	5%	50%	25%	18,180.00	4,347.29	JOD 2,687,458,265.89	3,742,872.37	723,263.45	5,704,566.23	11,409,132.47	19,295,703	219,680,519.84	-143,839,520
	10%	45%	30%	13,610.00	4,587.64	JOD 2,278,528,399.11	3,765,370.43	1,446,096.43	7,055,864.03	10,583,796.05	19,295,703	186,253,423.75	-210,925,544
	15%	40%	35%	10,760.00	4,848.13	JOD 2,045,626,535.01	3,770,854.34	2,169,829.48	8,498,977.31	9,713,116.93	19,295,703	167,215,359.70	-294,970,034
	20%	40%	35%	9,110.00	5,108.34	JOD 1,932,668,276.32	3,758,312.77	2,893,411.62	8,824,211.00	10,084,812.57	19,295,703	157,981,828.78	-386,867,537
	25%	35%	40%	7,110.00	5,380.94	JOD 1,787,187,630.28	3,774,099.82	3,616,219.66	10,400,356.25	9,100,311.72	19,295,703	146,089,824.97	-480,877,725
100%	0%	75%	25%	1,210,900.00	5,788.47	JOD 122,247,693,324.63	550,891	0	5,305,082.21	15,915,246.64	19,295,703	9,992,875,856	-9,906,888,187
	5%	60%	40%	708,900.00	6,124.38	JOD 72,114,875,010.98	296,724.93	964,729.74	8,713,999.68	13,070,999.52	19,295,703	5,894,875,999.37	-5,928,201,811
	10%	50%	50%	302,900.00	6,398.93	JOD 31,569,785,361.83	302,105.38	1,929,524.97	11,143,268.52	11,143,268.52	19,295,703	2,580,604,487.02	-2,738,728,043
	15%	55%	45%	200,900.00	6,732.17	JOD 21,436,434,070.30	214,175.40	2,894,247.99	10,484,802.66	12,814,758.80	19,295,703	1,752,275,389.70	-2,037,479,589
	20%	60%	40%	173,700.00	7,061.39	JOD 18,782,277,097.73	192,373.87	3,859,024.10	9,725,034.35	14,587,551.52	19,295,703	1,535,317,012.75	-1,951,142,564
	25%	65%	35%	138,900.00	7,386.57	JOD 15,367,314,444.10	179,039.39	4,823,856.84	8,863,963.60	16,461,646.68	19,295,703	1,256,168,204.93	-1,802,396,570

TABLE 3: Optimum ESS values at different energy types' cost for η=90% and 15 years lifetime.

ESS System, η =90%, i.e. BESS, ESS Life time 15 years.													
RE Mix	Curtailment Ω	PV%	W%	ESS Energy Size MWH	ESS Power Size MW	ESS CAPEX JOD	Fossil Fuel MWH	Curtailed Energy MWH	Wind Energy MWH	Solar Energy MWH	Sold Energy MWH	ESS CAPEX Annuity	Annuity Cash In JOD
20%	0%	13%	7%	53.00	3,482.51	JOD 881,228,055.28	13,862,047	0	1,901,781.45	3,531,879.83	19,295,703	102,953,473	128,638,174
	5%	20%	0%	0.00	0.00	JOD 0.00	13,710,537.90	21,077.14	0.00	5,606,246.52	19,295,703	0.00	243,596,077
	10%	19%	1%	0.00	0.00	JOD 0.00	13,527,407.80	17,362.23	289,283.06	5,496,378.20	19,295,703	0.00	242,387,580
	15%	19%	1%	0.00	0.00	JOD 0.00	13,370,913.68	26,358.62	297,557.64	5,653,595.18	19,295,703	0.00	241,481,588
	20%	18%	2%	0.00	0.00	JOD 0.00	13,184,157.81	21,112.74	613,266.20	5,519,395.81	19,295,703	0.00	240,294,535
	25%	18%	2%	0.00	0.00	JOD 0.00	13,018,642.80	31,669.51	630,873.55	5,677,861.94	19,295,703	0.00	239,122,933
25%	0%	17%	8%	910.00	3,482.51	JOD 1,052,628,055.28	12,992,115	0	2,017,216.82	4,286,585.74	19,295,703	122,978,057	110,022,698
	5%	21%	4%	0.00	0.00	JOD 0.00	12,798,713.90	23,332.28	1,043,252.20	5,477,074.06	19,295,703	0.00	237,716,316
	10%	20%	5%	0.00	0.00	JOD 0.00	12,573,569.62	23,720.21	1,349,171.72	5,396,686.90	19,295,703	0.00	235,918,437
	15%	20%	5%	0.00	0.00	JOD 0.00	12,392,720.02	35,824.12	1,387,763.08	5,551,052.33	19,295,703	0.00	234,410,616
	20%	19%	6%	0.00	0.00	JOD 0.00	12,149,006.22	39,630.15	1,724,720.38	5,461,614.53	19,295,703	0.00	231,946,825
	25%	18%	7%	0.00	0.00	JOD 0.00	11,945,843.32	42,792.99	2,069,944.84	5,322,715.31	19,295,703	0.00	229,402,232
50%	0%	43%	7%	14,498.00	3,482.51	JOD 3,770,228,055.28	8,611,170	0	1,629,672.32	9,234,809.83	19,295,703	440,474,028	-204,141,458
	5%	25%	25%	654.00	3,482.51	JOD 1,001,428,055.28	8,732,755.08	482,155.86	5,528,263.11	5,528,263.11	19,295,703	116,996,383.98	32,345,036
	10%	25%	25%	0.00	0.00	JOD 0.00	8,457,151.56	741,913.58	5,791,513.74	5,791,513.74	19,295,703	0.00	112,308,356
	15%	25%	25%	0.00	0.00	JOD 0.00	8,143,128.77	923,898.94	6,039,627.45	6,039,627.45	19,295,703	0.00	85,794,457
	20%	23%	27%	0.00	0.00	JOD 0.00	7,823,174.71	1,066,025.14	6,897,823.06	5,643,673.41	19,295,703	0.00	60,203,491
	25%	23%	27%	0.00	0.00	JOD 0.00	7,555,213.19	1,255,145.50	7,149,351.10	5,849,469.08	19,295,703	0.00	32,543,043
75%	0%	65%	10%	41,800.00	4,003.81	JOD 9,360,953,188.73	4,219,720	0	2,085,284.46	13,554,349.00	19,295,703	1,093,635,901	-873,151,915
	5%	50%	25%	13,790.00	3,908.14	JOD 3,735,034,571.19	4,321,681.27	723,447.67	5,345,351.54	10,690,703.08	19,295,703	436,362,389.27	-328,119,324
	10%	45%	30%	10,530.00	4,231.71	JOD 3,163,927,870.09	4,211,803.69	1,446,267.34	6,719,870.51	10,079,805.76	19,295,703	369,640,253.27	-368,321,681
	15%	40%	35%	7,850.00	4,526.82	JOD 2,701,704,862.46	4,235,207.57	2,170,340.95	8,134,887.70	9,297,014.52	19,295,703	315,638,949.63	-422,122,649
	20%	35%	40%	5,880.00	4,822.83	JOD 2,381,708,582.73	4,238,118.52	2,892,942.15	9,652,787.01	8,446,188.63	19,295,703	278,253,929.89	-494,056,834
	25%	35%	40%	4,630.00	5,087.46	JOD 2,197,865,340.38	4,235,488.48	3,617,248.07	10,029,849.00	8,776,117.88	19,295,703	256,775,607.55	-575,437,519
100%	0%	70%	30%	1,128,500.00	5,460.07	JOD 227,065,018,630.96	513,350	0	6,062,951.10	14,146,885.90	19,295,703	26,527,902,798	-26,382,058,896
	5%	60%	40%	632,700.00	5,856.19	JOD 128,004,047,891.29	307,238.89	964,715.84	8,424,629.58	12,636,944.36	19,295,703	14,954,654,665.11	-14,941,200,983
	10%	45%	55%	438,700.00	6,297.43	JOD 89,314,356,629.08	190,181.37	1,929,484.12	12,044,689.58	9,854,746.02	19,295,703	10,434,555,641.23	-10,568,061,273
	15%	40%	60%	368,000.00	6,696.23	JOD 75,274,057,815.40	138,537.47	2,894,300.34	13,702,576.40	9,135,050.93	19,295,703	8,794,233,920.06	-9,070,232,558
	20%	40%	60%	332,100.00	7,049.67	JOD 68,182,416,271.69	129,720.98	3,859,135.67	14,262,594.74	9,508,396.49	19,295,703	7,965,720,665.66	-8,378,305,456
	25%	35%	65%	315,100.00	7,450.39	JOD 64,882,596,987.78	133,719.50	4,823,840.54	16,054,704.62	8,644,840.95	19,295,703	7,580,204,280.35	-8,139,325,351

 ISSN (Online): 2790-7678
ISSN (Print): 2790-766X

In order to represent ESS sizes versus the annual revenues of implementing ESS solution in graphical form, 75% RE penetration is selected as an example to illustrate the relation between ESS size and RE mixture (PV% and W %), curtailed energy and annual revenue.

Figure 4 shows the relation between ESS size and RE mixture at different levels of curtailments. In the same figure, on a different axis, the Annual revenue for each level of curtailment is added.

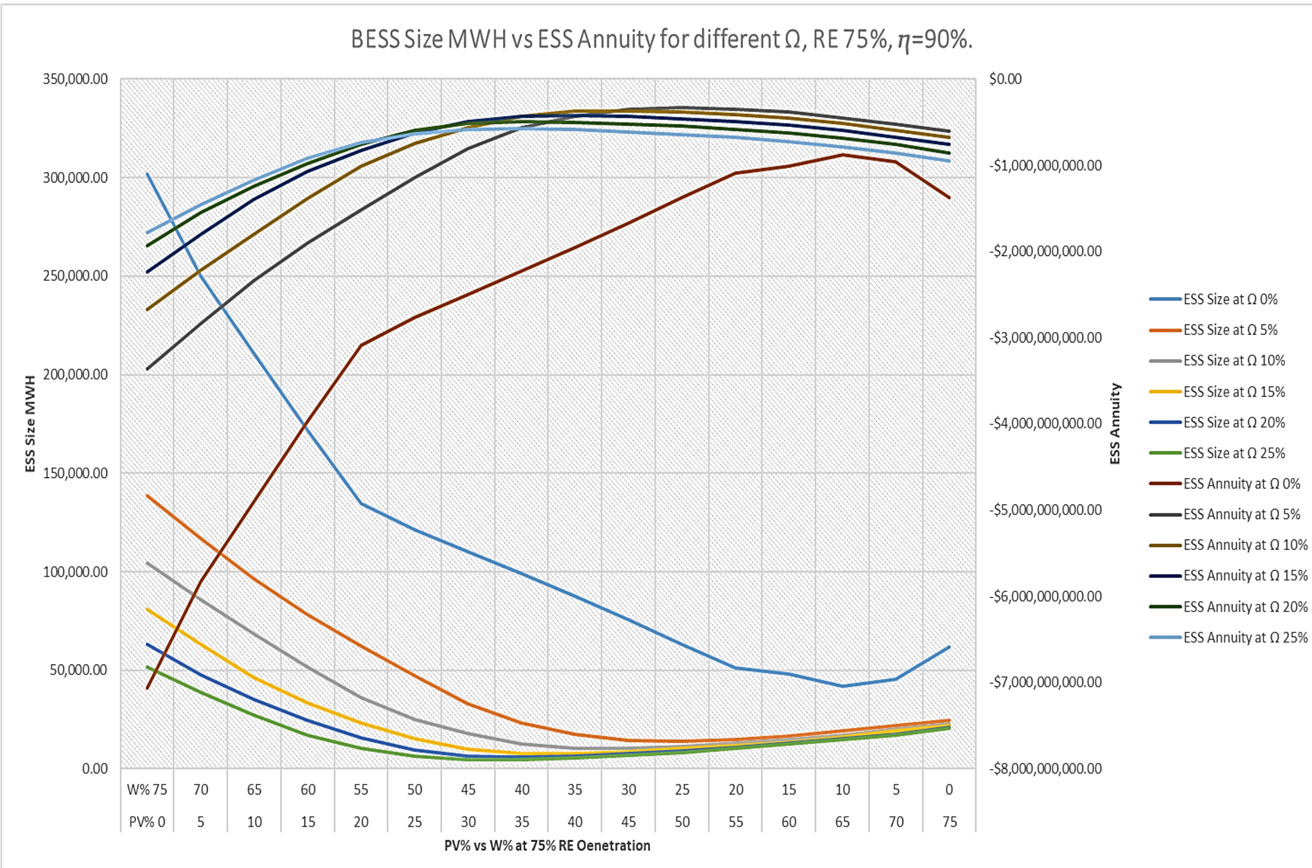

FIGURE 4: BESS Size in MWH and Annuity value for different curtailments at 75%% RE Penetration and 90% System Efficiency

Figure-5 shows the optimum ESS value at 5% curtailment curve of the same figure-4 after removing all other curtailment curves.

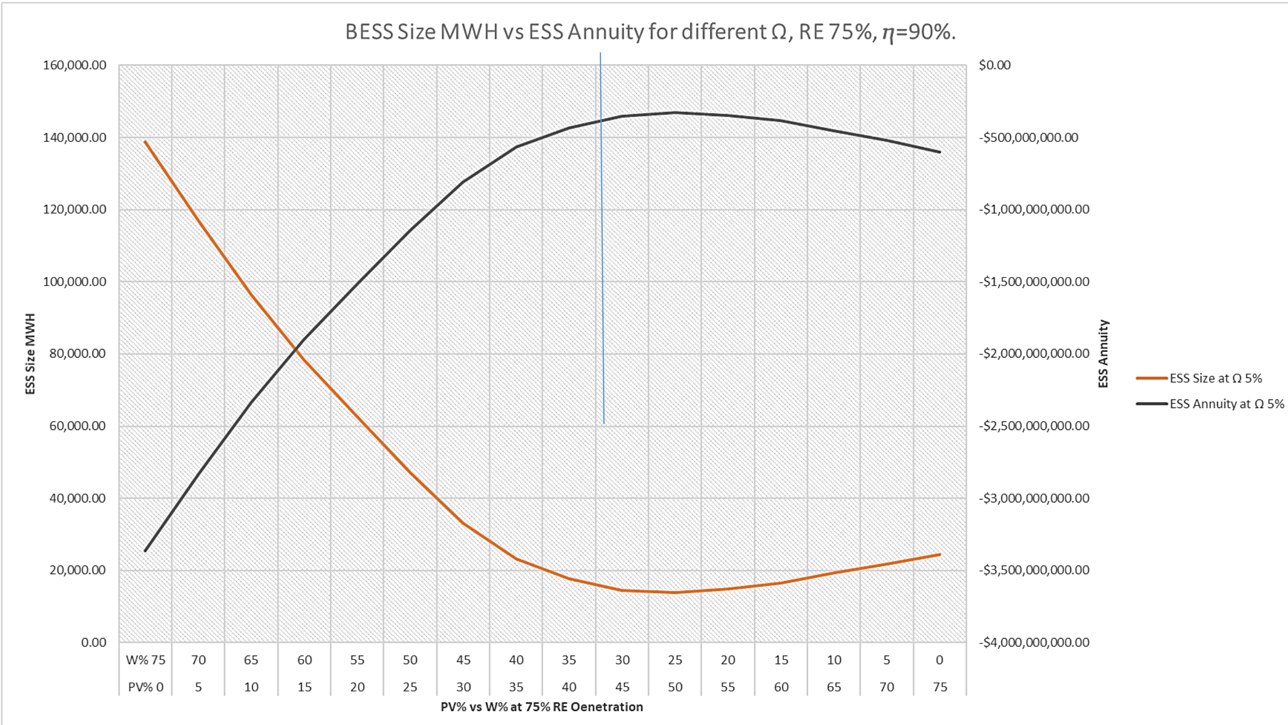

FIGURE 5: BESS Size in MWH and Annuity value for 5% curtailment at 75%% RE Penetration and 90% System Efficiency

To understand the ESS behaviour during the daily operation, Figure-6 illustrates the daily profiles of demand, fossil supply, solar energy supply, wind energy supply and ESS charging-discharging cycles for RE 75% at 50% PV, 25% W, **Ω**=5%, η=90% and 13,790MWH/ 3908MW BESS.

Required load demand shall be met by different available energy supplies, any extra energy due to renewable shall be stored in BESS until it is fully charged and any further extra RE energy will be curtailed [5-7].

In the case of less RE supply, BESS shall discharge and supply the network to meet the required load demand, any further shortage shall be supplied using fossil fuel energy.

Positive part of BESS MWH curve means the store is charging [8]. When RE is greater than load demand, the store starts storing this extra energy until it is full of energy, if more energy is available, it will be curtailed or in different words will be wasted (yellow line), this clearly shown in Figure-7, once BESS is fully charged, i.e. 13,790MWH, extra energy is curtailed [9-11].

ISSN (Online): 2790-7678
ISSN (Print): 2790-766X

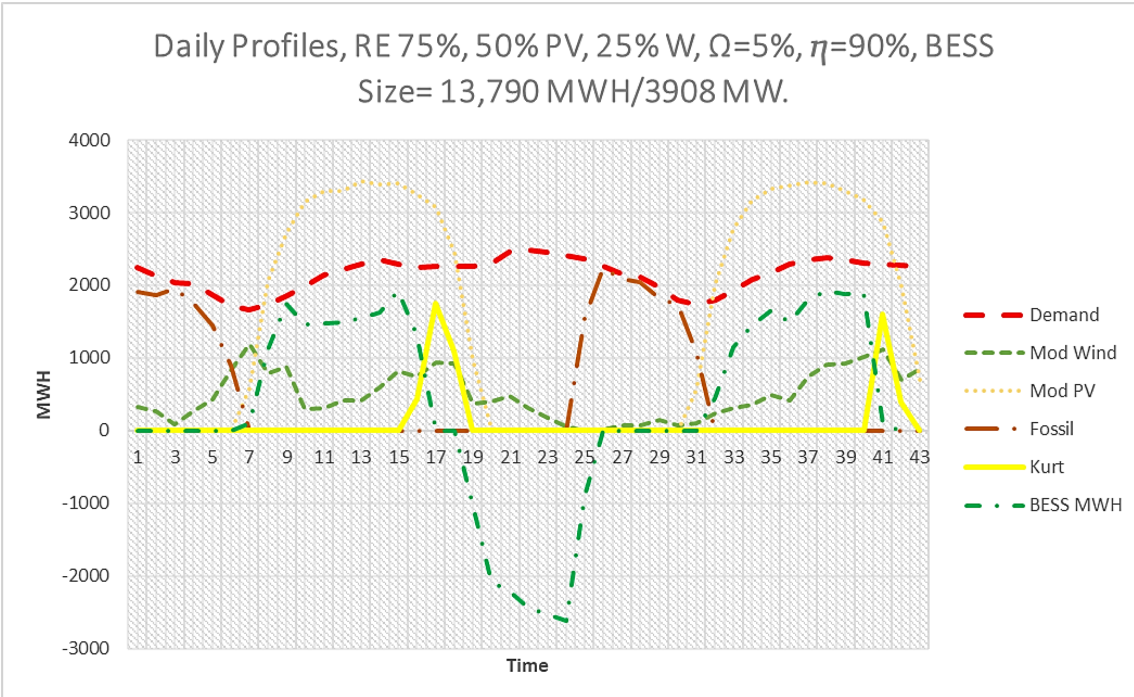

FIGURE 6: Daily profiles Demand, Solar, Wind, Fossil, Curtailed Energy and BESS Status (Charging-Discharging).

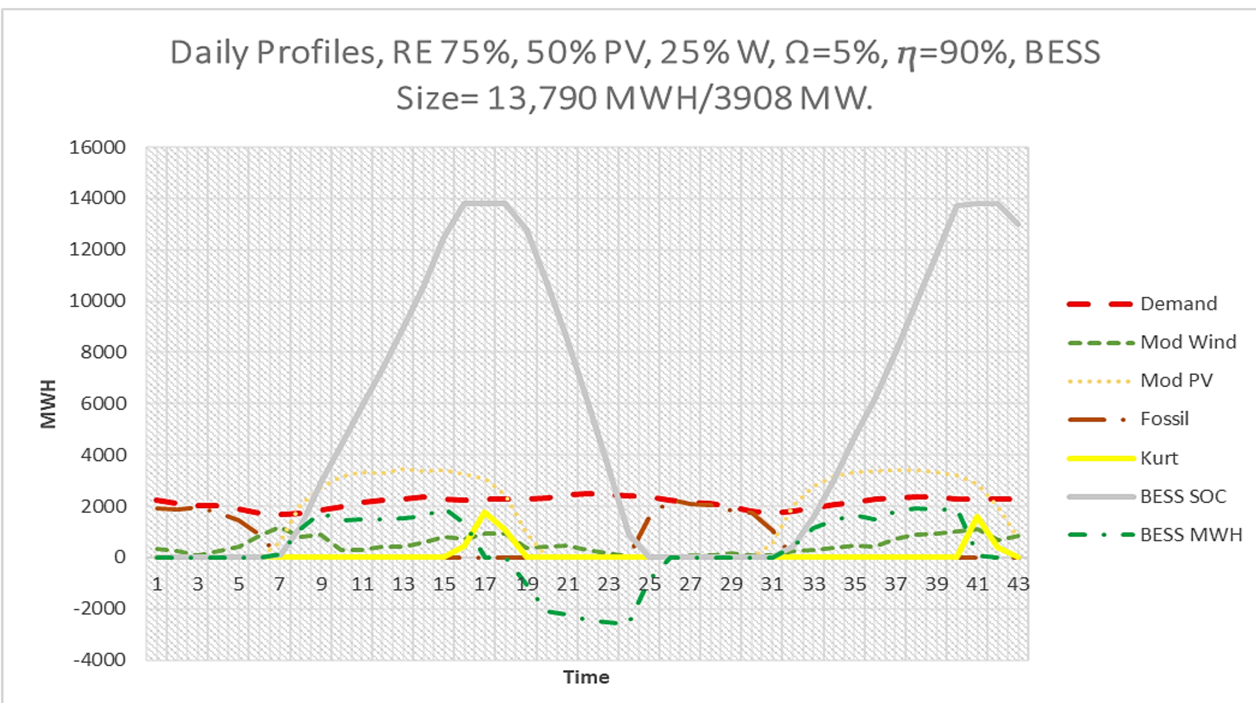

FIGURE 7: Daily profiles Demand, Solar, Wind, Fossil, Curtailed Energy, BESS Status (Charging-Discharging) and BESS Energy content.

How to reach zero carbon emissions?

Table-5 shows the estimated ESS size required to reach the zero carbon emissions at current RE prices, as this solution is not feasible, another four cases of reduced pieces are listed.

TABLE 4: BREAKEVEN PRICES FOR 100% RE PENETRATION, DIFFERENT CASES COMPARED TO THE CURRENT PRICES.

Type of Energy cost/price	Unit	Current Cost/Prices	Targeted Cost/Prices Case-1	Targeted Cost/Prices Case-2	Targeted Cost/Prices Case-3	Targeted Cost/Prices Case-4
Cost of ESS Energy Size	JOD/MWH	100000	48,836.22	25,618.49	57,883.46	51,082.80
Cost of ESS Power Size	JOD/MW	200000	189,116.63	184,177.84	191,041.13	189,594.52
Cost of Fossil Fuel Energy	JOD/MWH	65.2	64.86	64.70	64.92	64.87
Cost of Solar Energy	JOD/MWH	62.55	33.53	20.36	38.66	34.80
Cost of Wind Energy	JOD/MWH	70.2	50.52	41.58	54.00	51.38
Cost of Over-generation(waste energy)	JOD/MWH	77.21	116.09	77.21	77.21	77.21
Selling Price of Cosnumed Energy	JOD/MWH	77.21	116.09	77.21	77.21	77.21
CO2 reduction monitization	JOD/MWH	0.00	0.00	0.00	0.00	24.36
Social impact value of RE Projects	JOD/MWH	0.00	0.00	0.00	30.87	0.00
ESS Solution after applying the new prices						
RE Mixture, PV vs W	%	65% PV vs 35% W	55% PV vs 45% W	55% PV vs 45% W	65% PV vs 35% W	65% PV vs 35% W
Curtailment Percentage	%	0.25	0.15	0.15	0.25	0.25
ESS Energy Size	MWH	138,900.00	200,900.00	200,900.00	138,900.00	138,900.00
ESS Power Size	MW	7,386.57	6,732.17	6,732.17	7,386.57	7,386.57
Total Annuity	JOD	-1,802,396,570.23	24,726,968.69	33,568,997.10	0.00	0.00

To investigate the effectiveness of the proposed protection scheme, a simple real distribution system is chosen. To investigate the effectiveness of the proposed protection scheme, a simple real distribution system is chosen. To investigate the effectiveness of the proposed protection scheme, a simple real distribution system is chosen [12-15].

5. Conclusions:

Renewable energy generation became an essential part of the electrical networks helping the conventional fossil fuel energies to meet load demands [16]. However, due its intermittency behaviour, electrical network operators still depend on fossil fuel generation to meet the varying load demands. This could be overcome by introducing Energy Storage techniques to absorb the RE intermittency and variability, i.e. when excess of RE energy exists, ESS is charged and when shortage of energy appears, ESS discharge to meet this shortage [17-20].

As RE penetration level increases the ESS size required increases, i.e. at 100% RE penetration (almost zero carbon emissions) and 5% curtailment, we need to install 708,900.00 MWH ESS (JOD 72,114,875,010.98) at 60%PV and 40% Wind, compared to Zero ESS at 20% RE penetration level.

Even though 100% RE penetration could be achieved by introducing ESS solution in electrical network, still the fossil fuel generation is considered as essential part of the generation system to avoid electrical network stability issues in case of RE generation shortage as it is varying according to weather conditions such as solar irradiation and wind velocity.

ISSN (Online): 2790-7678
ISSN (Print): 2790-766X

Using high efficiency ESS allow for ESS size reducing, but this should be evaluated in combination of other factors, such as ESS life time and initial CAPEX. In this paper, it was noticed that using PHES with 80% efficiency would be feasible more than using BESS with 90% efficiency, as PHES lifetime can reach 50 years compared to 15 years lifetime of BESS. As an example, for 50% RE penetration with 5% Curtailment, the required ESS size at 25% PV and 25% Wind is 3,280.00 MWH for 80% Efficiency system compared to 654 MWH of 90% Efficiency system. From economical point of view, applying the PHES would be more feasible; BESS required CAPEX is JOD 1,001,428,055.28 with annual revenue of JOD 32,345,036.36, while the PHES CAPEX is JOD 1,111,565,249.75 and annual revenue could reach JOD 51,213,601.67.

The most feasible solution among all proposed mixtures and allowed curtailment based on the current RE prices, is to have 20% RE penetration level, with 5% allowed curtailment, 15% Solar percentage, 5% Wind percentage, in this case no need for ESS system, i.e. RE can be absorbed within the network easily, but with small amount of curtailment.

It is still feasible to have more RE penetration level and hence reduce more carbon, i.e. it is possible to go up to RE 50% penetration level (23% PV, 27% Wind) and with 0 ESS Size, but with 20% curtailment, i.e. 20% of produced RE will be wasted. With 50% RE penetration (28% PV, 22% Wind), if ESS with 3,400.00MWH/3,917.83MW and JOD 1,123,565,249.75 CAPEX is selected with 5% allowed curtailment, then this combination would be more feasible than not having ESS system.

Finally, RE prices, ESS initial costs and ESS life time has a significant effect on carbon zero emission target, i.e. current prices are considered high and need to be furtherly reduced as proposed in table-5 in order to allow for more RE penetration.

REFERENCES

[1] National Electric Power Company, Annual Reports, Published on NEPCO website.

[2] National Electric Power Company, official website, http://www.nepco.com.jo/.

[3] Bruno Cárdenas, Lawrie Swinfen-Styles, James Rouse, Adam Hoskin, Weiqing Xu, S.D. Garvey, Energy storage capacity vs. renewable penetration: A study for the UK, Renewable Energy, Volume 171, 2021, Pages 849-867, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2021.02.149.

[4] Suhil Kiwan, Elyasa Al-Gharibeh, Jordan toward a 100% renewable electricity system, Renewable Energy, Volume 147, Part 1, 2020, Pages 423-436, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2019.09.004.

[5] J. A. Taylor, D. S. Callaway and K. Poolla, "Inventory control of storage in distribution systems," 2012 American Control Conference (ACC), Montreal, QC, Canada, 2012, pp. 2147-2152.

[6] J. Tan and Y. Zhang, "Coordinated Control Strategy of a Battery Energy Storage System to Support a Wind Power Plant Providing Multi-Timescale Frequency Ancillary Services," in IEEE Transactions on Sustainable Energy, vol. 8, no. 3, pp. 1140-1153, July 2017. 52.

[7] T. M. Al-Jaafreh, A. Al-Odienat and Y. A. Altaharwah, "The Solar Energy Forecasting Using LSTM Deep Learning Technique," 2022 International Conference on Emerging Trends in Computing and Engineering Applications (ETCEA), Karak, Jordan, 2022, pp. 1-6, doi: 10.1109/ETCEA57049.2022.10009717. 50.

[8] Khaled Alawasa Distributed Energy Resources Electrical Systems: Future prospective, Jordan Journal of Energy (JJE), Volume1, Number 1, 2023.

[9] Kandari, R.; Neeraj, N.; Micallef, A. Review on Recent Strategies for Integrating Energy Storage Systems in Microgrids. Energies 2022, 16, 317.

[10] Fu, Q.; Fu, C.; Fu, P.; Deng, Y. Energy Storage Technology Used in Smart Grid. J. Physics Conf. Ser. 2021, 2083, 032067. 53.

[11] R. Al-Rawashdeh, M. Alsarayreh, "Solar Photovoltaic Forecasting Using ANN Network for Central and Southern Regions of Jordan," 2023 IEEE Jordan International Joint Conference on Electrical Engineering and Information Technology (JEEIT), Amman, Jordan, 2023, pp. 50-57, doi: 10.1109/JEEIT58638.2023.10185900.

[12] Wei, P.; Abid, M.; Adun, H.; Awoh, D.K.; Cai, D.; Zaini, J.H.; Bamisile, O. Progress in Energy Storage Technologies and Methods for Renewable Energy Systems Application. Appl. Sci. 2023, 13, 5626.

[13] T. M. Al-Jaafreh , "The Application of Deep Learning Techniques for Solar Power Forecasting," 2022 13th International Conference on Information and Communication Systems (ICICS), 2022, pp. 214-219, Irbid, Jordan, June 21-23, 2022.

[14] Katsanevakis, M.; Stewart, R.A.; Lu, J. Aggregated applications and benefits of energy storage systems with application-specific control methods: A review. Renew. Sustain. Energy Rev. 2017, 75, 719–741.

[15] Eyer, J.; Corey, G. SANDIA REPORT Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide AStudy for the DOE Energy Storage Systems Program. Available online.

[16] He, L.; Jiang, X.; Tang, C.; Liu, Y.; Wu, Y.; Weilin, L. Energy Management Strategy of Composite Energy Storage System With Airborne High-power Pulse Load. In Proceedings of the 2022 IEEE 17th Conference on Industrial Electronics and Applications (ICIEA), Chengdu, China, 16–19 December 2023; pp. 219–224.

[17] Fraihat H, Almbaideen A, Al-Odienat A, Al-Naami B, De Fazio R, Visconti P. “Solar Radiation Forecasting by Pearson Correlation Using LSTM Neural Network and ANFIS Method: Application in the West-Central Jordan.” Future Internet. 14 (3):79, 2022.

[18] Viswanathan, V.; Mongird, K.; Franks, R.; Li, X.; Sprenkle, V.; Baxter, R. 2022 Grid Energy Storage Technology Cost and Performance Assessment. 2022. Available online: https://www.energy.gov/eere/analysis/2022-grid-energy-storage-technology-cost-and-performance-assessment (accessed on 6 March 2024).

[19] Abbas, A.; Halbe, S.; Chowdhury, B. Comparison of Peak Demand Shaving Potential of Demand Response and Distributed Energy Storage in Residential Buildings. In Proceedings of the SoutheastCon 2019, Huntsville, Alabama, 11–14 April 2019; pp. 1–6.

[20] Mohd, A.; Ortjohann, E.; Schmelter, A.; Hamsic, N.; Morton, D. Challenges in integrating distributed Energy storage systems into future smart grid. In Proceedings of the 2008 IEEE International Symposium on Industrial Electronics (ISIE 2008), Cambridge, UK, 30 June–2 July 2008; pp. 1627–1632.