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Comparison of PV-Battery Architectures for Residential Applications

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***Abstract*—The paper provides a comparison of four PV-battery architectures with dc and ac backbones, in terms of autarky, energy efficiency, battery size and reduction of annual electricity cost. The comparison is conducted based on the residential load and irradiation data from the Netherlands. The effect of different PV generation is also analyzed by comparing the results with irradiation data from Costa Rica. The results show that the ac coupled architecture gives the best performance.**

NOMENCLATURE

EEA	Electrical Energy Autarky
E_{grid_drawn}/ E_{grid_fed}	Energy drawn/fed from/to the grid throughout the year during base and off-peak times
E_{load}	Energy demanded throughout the year
E_{PV}	PV energy generated throughout the year
η_{batt}	Efficiency of battery
η_{conv_batt}	Efficiency of converter attached to battery
η_{conv_PV}	Efficiency of converter attached to PV
η_{inv}	Efficiency of inverter
η_{inv_batt}	Efficiency of inverter attached to battery
η_{inv_PV}	Efficiency of inverter attached to PV
P_{batt_charge}	Power used to charge the battery
$P_{batt\_discharge}$	Power discharged from the battery
P_{grid_drawn}	Power drawn from the grid
P_{grid_fed}	Power fed to the grid
P_{load}	Power demand (ac and dc)
P_{load_ac}	AC power demand
P_{load_dc}	DC power demand
P_{PV}	Power generated from PV
SOC	State of Charge

I. INTRODUCTION

Electricity production using PV panels is one of the most practical choices for households to minimize the electricity bill and also lower energy dependencies on fossil fuel. However, PV power is still considered as an unreliable source due to its dependence on irradiance and temperature [1]. Implementing PV generation system for a household requires supporting electrical components e.g. battery, and converters. The battery is needed due to the mismatch between PV power generation and the load demand. Using a battery at its optimum size will reduce the annual electricity cost [2], reduce line losses, and minimize intermittency of PV generation [3]. Furthermore, integrating PV and battery into the system reduces the dependency of the system on the grid.

There are several methods to integrate PV and battery for households. Different PV-battery architectures have been proposed. These architectures differ in converter arrangements, conversion steps, and ac/dc bus utilization.

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This paper presents the comparison of PV-battery architectures in terms of autarky, saving estimations, and system efficiency, followed by the optimum battery size for the system. Section II describes different PV-battery architectures that were analyzed. Section III shows the load profile, PV profile for the Netherlands and Costa Rica, and the power flow implemented on MATLAB Simulink model. In section IV, the autarky of each architecture based on the simulation results is shown. Section V presents the comparison for each architecture regarding autarky, saving estimations, and system efficiencies. In section VI, the best architecture based on aspects above is determined.

II. PV-BATTERY ARCHITECTURES

Four different PV-battery architectures are considered, as depicted in Fig. 1. The 1st, 2nd, and 4th architecture utilize a dc grid as the interconnection with 400V dc bus voltage. The 3rd architecture utilizes 230V ac bus voltage. The battery used are 400V Li-ion with different capacities to be analyzed in the later sections. The initial SOC is set to 50%. Specific PV panels are utilized in the simulations, i.e. Sunpower E20/435. This paper only compares the energy utilization regarding autarky, energy efficiency, and storage size for each system. Therefore, the arrangements of PV and voltage set-points is not discussed.

1) *In line*

This 1st architecture is an arrangement in which the PV arrangement (panels and dc/dc converter) and the battery are connected in parallel, with the battery being directly connected to the dc bus as can be seen in Fig. 1a) [4]. This configuration requires one unidirectional dc/dc converter and a dc/ac inverter. The power from the PV panels will go through the dc/dc converter and then through the inverter to reach the load and/or grid. The PV power that goes into the battery passes first through a dc/dc converter. Power from the battery to the load goes through the inverter. Power drawn from the grid can be directly used by the load.

2) *DC coupled*

The 2nd architecture, dc Coupled, is an arrangement in which the PV arrangement and the battery are connected in a parallel configuration as can be seen in Fig. 1b). This requires two dc/dc converters (one unidirectional and one bidirectional) to connect the PV panel and battery to the dc Bus, and one unidirectional dc/ac inverter to connect dc bus with the load [5],[6].

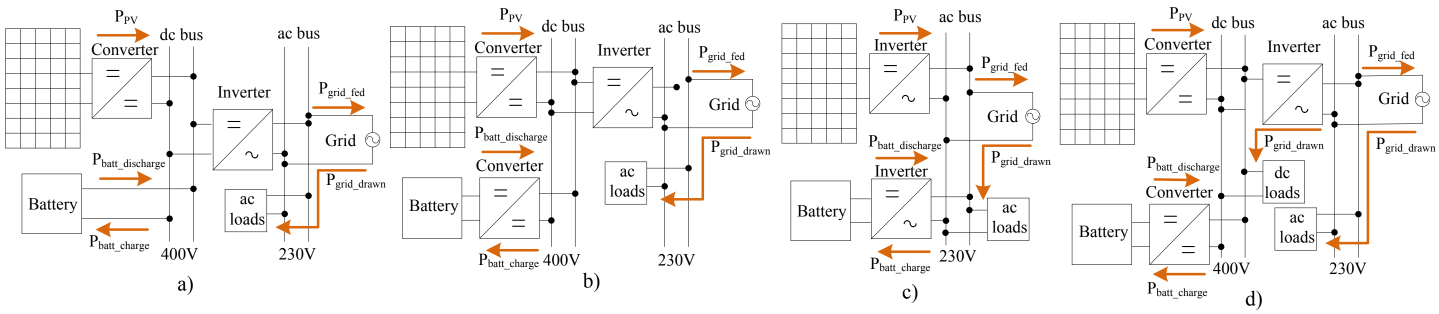

Figure 1. a) In line (1st), b) DC coupled architecture (2nd), c) AC coupled (3rd), and d) DC/AC coupled (4th)

3) *AC coupled*

The 3rd architecture is very similar to the 2nd architecture. However, this topology utilizes an ac bus as the interconnection between the PV panels, the battery, and the load [7]. The load is connected directly to the ac bus as can be seen in Fig. 1c). This arrangement requires a unidirectional dc/ac inverter from PV panel to ac bus and bi-directional dc/ac converter to connect the battery with ac bus. The power flow of PV and battery in this architecture differ from the 1st and 2nd architecture because the power that goes to the load and/or grid does not go through the central inverter. The power from PV is already converted into ac with the inverter that is connected directly with the PV. This is also applied to the power from and to the battery.

4) *DC/AC coupled*

The 4th topology is similar to the 2nd topology. However, this topology utilizes the dc bus directly for the dc load as can be seen in Fig. 1d). In this architecture, the power from PV and battery can be used for the dc load without going through the central inverter. However, if there is power shortage from PV and battery, the power from the grid has to go through a central inverter to go to the dc loads. For this architecture, the proportion of ac and dc load is set to 90% and 10% [8]. The influence of different ac and dc load percentage is reported in the Appendix.

III. Details of the Model

1) *Load*

The load profile throughout the year is based on the Dutch household [9], considering the variations due to seasonal changes, see Fig. 2. The load demand in the middle of the year is lower than that at the beginning and end of the year, which corresponds to high demand in winter. The same load is used in all the simulations. Total energy demanded by the load during the complete year is 3560kWh.

2) *PV generation*

The PV generation for the Netherlands (NL) and Costa Rica (CR) was calculated using Global Horizontal Irradiation (GHI), ambient temperature, wind speed, and cloud cover.

For the Netherlands, all data was taken from the KMNI (Koninklijk Nederlands Meteorologisch Instituut) at the Cesar Observatory (51.971N, 4.927E). In the case of Costa Rica, the data was provided by the IMN (Instituto Meteorológico Nacional), at CIGEFI station (9.56N, 84.02W). To estimate the module temperature, the model reported in [10] is used. In the Netherlands, there is high irradiation around summer (in the middle of the year) while in Costa Rica, the irradiation is more or less constant throughout the year. The number of panels depends on the solar energy that can be farmed throughout the year. Therefore, the amount of PV panels required for both conditions is different. The required PV panels are calculated by matching the load and the PV generation throughout the year. The Netherlands receives less irradiance than Costa Rica, which results in higher amount of required PV panels to be able to match the load over the year.

a) *The Netherlands*

Ten PV panels rated 3.5kW$_p$ are needed to provide almost the same energy (3563kWh) to the load throughout the year. The PV generation profile can be seen in Fig. 3.

b) *Costa Rica*

Based on irradiation data from Costa Rica, it requires five PV panels to provide enough energy (3364kWh) for the load throughout the year. The PV generation profile (Fig. 4) differs from the PV generation in the Dutch case. The maximum PV power in Costa Rica is around 2.2kW$_p$ (5 panels) that provide the energy needed to satisfy the load. It is half of the amount of panels required in The Netherlands. The PV generation in Costa Rica is more or less constant whereas, in the Netherlands, which has four seasons, there is a high PV generation in the middle of the year and less PV generation at the beginning and end of the year. This fact is represented in the irradiation profile for the whole year.

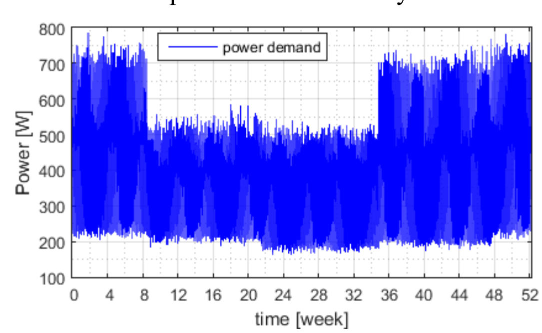

Figure 2. Load Profile

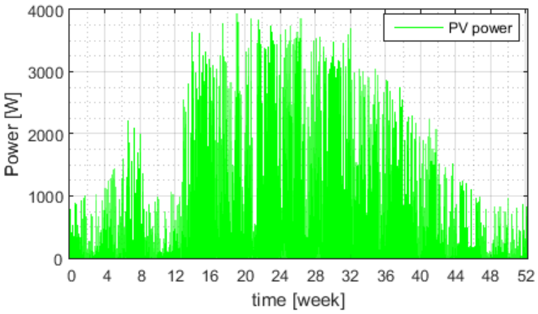

Figure 3. PV Generation (The Netherlands, 2014)

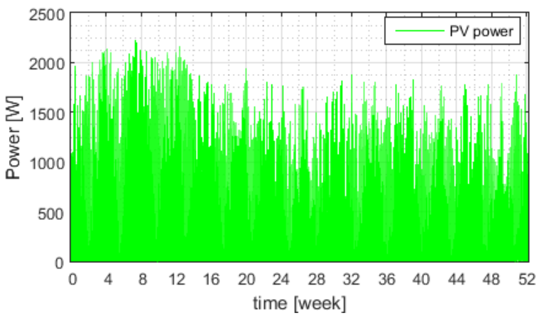

Figure 4. PV Generation (Costa Rica, 2014)

3) Power flow algorithm

The performance of each architecture is obtained using the following criteria:

Criteria:

1. SOC Limit: $20\% \leq SOC \leq 80\%$
2. Generation > Load
   $SOC \geq 80\%$: Power fed to the grid
   $20\% \leq SOC \leq 80\%$: Battery charged
3. Generation < Load
   $SOC \leq 20\%$: Power drawn from grid
   $20\% \leq SOC \leq 80\%$: Battery discharged

Table I presents the power flow algorithm for each architecture. The different algorithms represent the various conversion steps and converter arrangements. As can be seen in equations from Table I, there are conversion losses for the power that goes through the converters. For the 1st architecture, the conversion losses come from η_{conv_PV} and η_{inv} ((1)-(4)). For the 2nd architecture, the conversion losses come from η_{conv_PV}, η_{conv_batt}, and η_{inv} ((5)-(8)). The losses in the 3rd architecture are related to η_{inv_PV} and η_{inv_batt} ((9)-(12)). In the 4th architecture, almost similar conversion losses to the 2nd occur. There are different algorithms especially for the power drawn from the grid as can be seen in (13)-(17).

The efficiency of the converters depend on the power input; it changes according to the power-efficiency curve of the converter. For the battery, the efficiency is set to 97% [11] and the losses come from the conversion when the electrical energy goes into the battery and losses when the electrical energy is taken out from the battery. These losses are due to the conversion of electrical energy into chemical energy stored in the battery and vice-versa. The constant battery efficiency is justified because the energy exchange with the battery for every architecture is nearly equal (as can be seen Fig.16 and Fig. 17 in Appendix).

4) Case of zero energy fed to the grid

The battery capacity depends on the amount of energy that has to be stored, which also corresponds to the deviation of power produced and load demand profile throughout the year. In the case of 100% self-consumption, in which all the PV energy has to be stored in the battery and avoid feeding any energy into the grid (by using a huge battery), the SOC in The Netherlands and Costa Rica gives different profile as can be seen in Fig. 5. The battery is sized in a way that the SOCs are above 78% but do not reach 80%. The battery size for 100% self-consumption for all the architectures in the Netherlands and Costa Rica can be seen in Table II.

For the Dutch case, the battery SOC has its highest value around middle-end of the year, which is when the irradiation is high, and the load is low (Fig. 3 and Fig. 4). However, in Costa Rica, the battery SOC reaches its highest value at the beginning of the year when the irradiation is higher, but the load demand is low, as can be seen in Fig. 5. In Costa Rica, the PV profile is different than in the Netherlands. Therefore, by using the same load profile as in the Netherlands, the SOC is expected to fluctuate between 20% and 80% over the year without a particular peak in the year.

Fig. 5 and Table II also show that there is more energy that has to be stored in the Netherlands than in Costa Rica due to a higher mismatch between solar power produced and load. Therefore, to have 100% self-consumption, it requires bigger battery size for the Netherlands than in Costa Rica.

TABLE I. POWER FLOW ALGORITHMS

Architecture I		
P_{batt_charge}	$(P_{PV} \times \eta_{conv\_PV} - P_{load} / \eta_{inv}) \times \eta_{batt}$	(1)
$P_{batt\_discharge}$	$(P_{PV} \times \eta_{conv\_PV} - P_{load} / \eta_{inv}) / \eta_{batt}$	(2)
P_{grid_drawn}	$P_{load} - P_{\_PV} \times \eta_{conv\_PV} \times \eta_{inv}$	(3)
P_{grid_fed}	$P_{PV} \times \eta_{conv\_PV} \times \eta_{inv} - P_{load}$	(4)
Architecture II		
P_{batt_charge}	$(P_{PV} \times \eta_{conv\_PV} - P_{load} / \eta_{inv}) \times \eta_{conv\_batt} \times \eta_{batt}$	(5)
$P_{batt\_discharge}$	$(P_{PV} \times \eta_{conv\_PV} - P_{load} / \eta_{inv}) / (\eta_{batt} \times \eta_{conv\_batt})$	(6)
P_{grid_drawn}	$P_{load} - P_{PV} \times \eta_{conv\_PV} \times \eta_{inv}$	(7)
P_{grid_fed}	$P_{PV} \times \eta_{conv\_PV} \times \eta_{inv} - P_{load}$	(8)
Architecture III		
P_{batt_charge}	$(P_{PV} \times \eta_{inv\_PV} - P_{load}) \times \eta_{inv\_batt} \times \eta_{batt}$	(9)
$P_{batt\_discharge}$	$(P_{PV} \times \eta_{inv\_PV} - P_{load}) / (\eta_{batt} \times \eta_{inv\_batt})$	(10)
P_{grid_drawn}	$P_{load} - P_{PV} \times \eta_{inv\_PV}$	(11)
P_{grid_fed}	$P_{PV} \times \eta_{inv\_PV} - P_{load}$	(12)
Architecture IV		
P_{batt_charge}	$(P_{PV} \times \eta_{conv\_PV} - P_{load\_ac} / \eta_{inv} - P_{load\_dc}) \times \eta_{conv\_batt} \times \eta_{batt}$	(13)
$P_{batt\_discharge}$	$(P_{PV} \times \eta_{conv\_PV} - P_{load\_dc} - P_{load\_ac} / \eta_{inv}) / (\eta_{conv\_batt} \times \eta_{batt})$	(14)
P_{grid_drawn}	$P_{load\_ac} - (P_{\_PV} \times \eta_{conv\_PV} - P_{load\_dc}) \times \eta_{inv}$, for $(P_{load\_DC} < P_{PV} < P_{load\_ac})$	(15)
	$P_{load\_ac} + P_{load\_dc} / \eta_{inv} - P_{\_PV} \times \eta_{conv\_PV}$, for $(P_{PV} \leq P_{load\_dc})$	(16)
P_{grid_fed}	$(P_{PV} \times \eta_{conv\_PV} - P_{load\_dc}) \times \eta_{inv} - P_{load\_ac}$	(17)

TABLE II. BATTERY SIZE FOR ZERO ENERGY FEED TO THE GRID

Architecture	Battery size [kWh]	
	NL	CR
1	1640	136
2	1460	88
3	1620	132
4	1480	92

5) Feed-in tariffs policy and time-of-use prices

Feed-in tariffs policy used for the saving, calculations are based on:

Base (09.00h - 20.00h) : € 0.2202 /kWh
Off-peak (01.00h - 08.00h; 21.00h - 24.00h) : € 0.2062 /kWh
Sold to Grid : € 0.092 /kWh

By implementing the PV system, it will reduce the power drawn from the grid because there is PV power that can be used for the loads. Therefore, the annual electricity bill will be reduced. The electricity bill is calculated over the year. The excess PV energy can be sold to the grid at the same price with the electricity cost from the grid until it offsets the cost (bought – sold equal to zero). Above that point, if the PV generates more energy, the electricity sold more than consumption can only be sold at the lower price. The reduction of electricity bill and the revenue from selling the electricity to the grid during the year can be considered as savings per year. Therefore, (18) is derived. Where S is savings, R is the electricity bill before using the PV, C is the new electricity cost after installing the PV, and T_i is selling tariff.

$$S = R - (C_{\text{base}} + C_{\text{off-peak}}) \tag{18}$$

Where,

$$C_{\text{base}} = (E_{\text{grid\_drawn\_base}} - E_{\text{grid\_fed\_base}})T_i \tag{19}$$

$i = 1,2$

$$C_{\text{off-peak}} = (E_{\text{grid\_drawn\_off\_peak}} - E_{\text{grid\_fed\_off\_peak}})T_i \tag{20}$$

$i = 1,3$

$i = 1$ when it becomes a net producer
$i = 2$ when it becomes net consumer at base time
$i = 3$ when it becomes net consumer at off-peak time

IV. AUTARKY

1) Concept

The system can be fully sustainable if it can be self-sufficient from the PV generation. However, to be able to provide power from PV for the whole load over the year, it will require much PV panels and a huge battery. The system has to be able to provide enough power even for the lowest irradiation level which is by adding, even more, PV panels. Furthermore, the battery has to store much energy during the day to be used later during the night. Autarky shows the degree of autonomy of the system by calculating Electrical Energy Autarky (*EEA*). This type of autarky only considers the electrical energy from the grid without taking into account the heat load demand and fuel consumption [12]. Higher EEA means that the system is more independent from the grid.

$$\%EEA = 100\frac{E_{\text{load}} - E_{\text{grid\_drawn}}}{E_{\text{load}}} \tag{21}$$

2) Optimum size

The battery size corresponds to several variables i.e. autarky, power drawn and fed to/from the grid, and capital cost. Higher battery size provides more space to store electrical energy. Therefore, more PV energy can be used (no need to dump the excess energy) and result in a more independent system of the grid. On the other hand, bigger battery requires a very significant increase in the capital cost. Therefore, optimum battery size is needed to get the best performance regarding autarky, savings, and system efficiency of the system at the lower capital cost.

V. COMPARISON

1) Autarky

a) Differentiated autarky (base and off peak)

According to Fig. 6 and Fig. 7, the bigger battery will provide higher EEA for base and off-peak time. It means that the higher the battery size, the more independent the system is from the grid, due to 100% self-consumption of PV generation. However, it requires a huge battery which is very costly.

These graphs also show the effect of seasons on the autarky. Even though in the Netherlands more PV panels are used, but the autarky is still lower than in Costa Rica. This is because in the beginning, and the end of the year the system in the Netherlands is dependent on the grid due to high load demand but low PV generation (see Fig. 2 and Fig. 3).

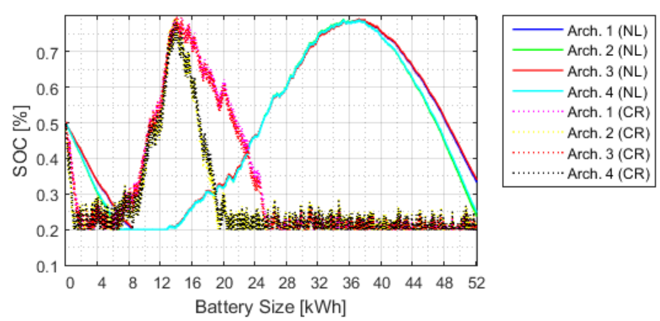

Figure 5. SOC 100% self-consumption for The Netherlands and Costa Rica

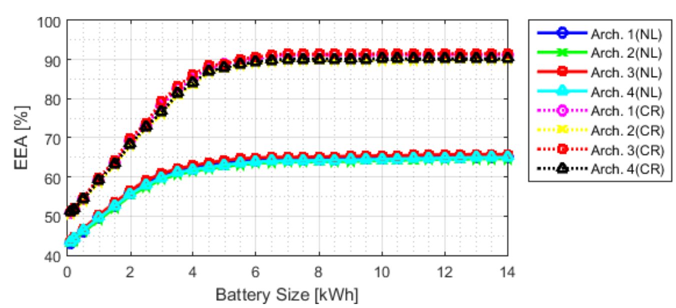

Figure 6. EEA Base the Netherlands and Costa Rica

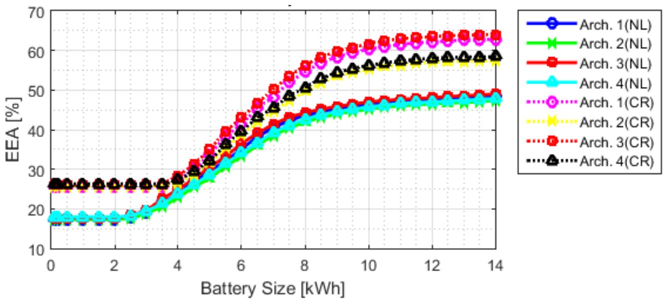

Figure 7. EEA off-peak the Netherlands and Costa Rica

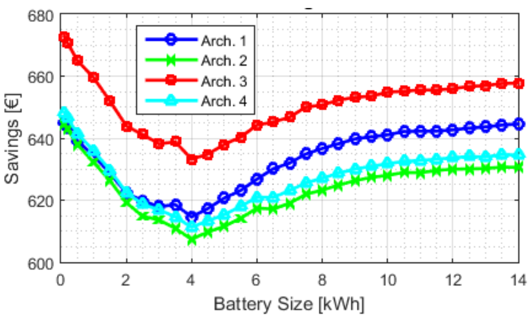

Figure 8. Savings (the Netherlands)

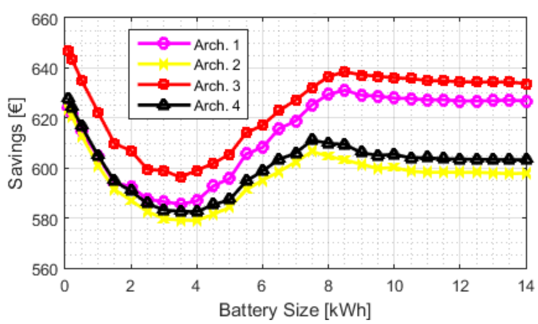

Figure 9. Savings (Costa Rica)

2) *Savings and System Losses*

Savings are calculated based on feed-in tariffs policy explained in section III. In the Dutch case, the highest savings is obtained when the systems are not using battery. However, in Costa Rica, except for architecture 1, highest savings are obtained by avoiding the utilization of a battery as can be seen in Fig. 8 and Fig. 9. The increasing amount of savings along with decreasing battery correlates with the quantity of energy drawn and fed from/to the battery. Decreasing battery size increases the energy drawn from the grid and also increase the energy fed to the grid. Although, the increase of energy fed to the grid is higher, as can be seen in Fig. 10 - Fig. 13. Therefore, according to the policy used in the calculation, there is an increment in the reduction of the annual electricity bill.

System losses are defined by the differences between the energy input and the energy used in the system. The energy that goes into the system is the energy produced from PV generation and the energy being drawn from the grid. The energy used in the system is the energy for the load and the energy that as being fed to the grid.

$$\%Losses = 100\frac{E_{\mathrm{PV}} + E_{\mathrm{grid\_drawn}} - E_{\mathrm{load}} + E_{\mathrm{grid\_fed}}}{E_{\mathrm{PV}} + E_{\mathrm{grid\_drawn}}} \quad (22)$$

According to Fig. 14 and Fig. 15, decreasing the battery size will reduce the system losses, and the smallest system losses are obtained by not using batteries in the system. Decreasing the battery size will increase the energy drawn ($E_{\mathrm{grid\_drawn}}$) and fed ($E_{\mathrm{grid\_fed}}$) from/ to the grid due to the smaller capability to store energy in the battery. However, in the case of the Netherlands and Costa Rica, the increase of $E_{\mathrm{grid\_drawn}}$ is lower than the rise of $E_{\mathrm{grid\_fed}}$. Therefore, the system losses are decreasing. Reducing battery size also reduces the system losses due to less energy going in and out of the battery, which means fewer losses from electrical-chemical energy conversion.

According to Fig. 6 and Fig. 7, in the Netherlands case, the 3rd architecture gives the highest autarky, on base (65% at 10kWh) and off-peak (47% at 14kWh). The highest savings is obtained in the 3rd architecture. However, it can only be obtained in the system without battery (€675 in the Netherlands). If the battery is included in the system, the highest savings is achieved in the 3rd architecture (Fig. 8). The smallest losses incurred is in the 3rd architecture as can be seen in Fig. 14. In Costa Rica case, according to Fig. 6 and Fig. 7 the highest base and off-peak autarky is given by the 3rd architecture. Similar to the case of the Netherlands, the 3rd architecture also gives the highest savings excluding battery (Fig. 9). Excluding battery from the system reduces the capital cost of installing the PV system. However, this gives trade-off with the autarky which becomes minuscule, and an enormous amount of energy are being dumped (wasted). The smallest losses are also given by the 3rd architecture as can be seen in Fig.15.

Based on Fig. 6, the optimum battery size to achieve high base EEA is around 2-4 kWh for Dutch case and 3-5 kWh for Costa Rica, Based on Fig. 7 to obtain high off-peak *EEA*, the optimum battery size is around 6-8 kWh and 7-9 kWh for the Netherlands and Costa Rica case. These optimum battery sizes are the points whereby increasing the battery size will gives smaller increment in *EEA*. This size gives a good estimation for a system with high *EEA*, saving, and system efficiency. Taking higher battery size will require higher cost without significant improvement regarding *EEA*, savings, and system efficiency of the system.

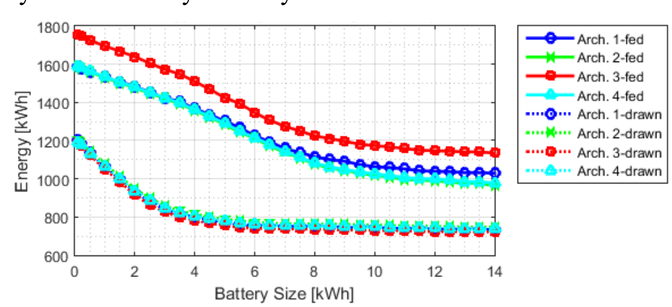

Figure 10. Energy exchange with the grid at base time (the Netherlands)

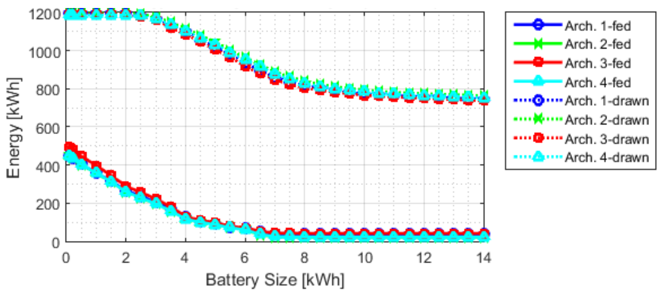

Figure 11. Energy exchange with the grid at off-peak time (the Netherlands)

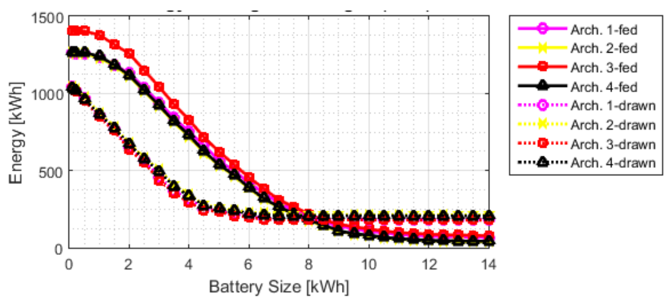

Figure 12. Energy exchange with the grid at base time (Costa Rica)

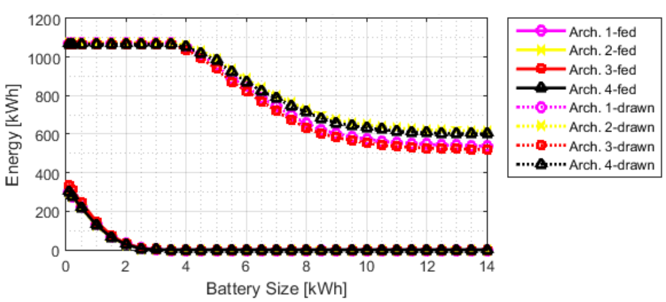

Figure 13. Energy exchange with the grid at off-peak time (Costa Rica)

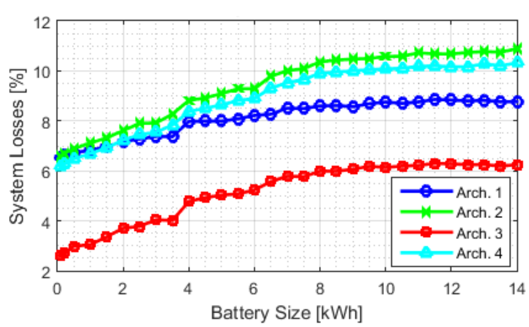

Figure 14. System Losses (the Netherlands)

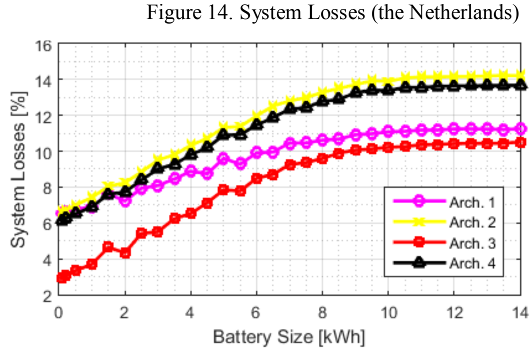

Figure 15. System Losses (Costa Rica)

VI. CONCLUSION

According to the results above, the 3rd architecture gives the best overall performance regarding autarky, savings, and system losses for both cases for the assumptions and conditions that were selected. The optimum battery size according to base and off-peak *EEA* is around 2-4 kWh and 6-8 kWh in the Netherland; 3-5 kWh and 7-9 kWh in Costa Rica.

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APPENDIX

1) *Energy charged and discharged from battery*

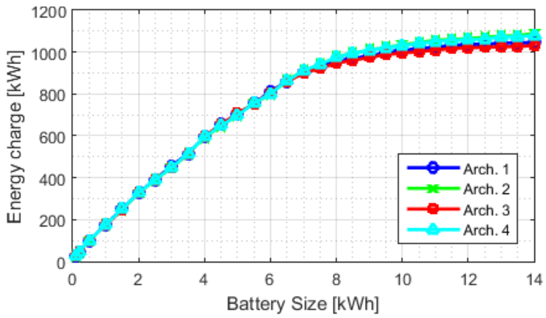

Figure 16. Energy charge to battery

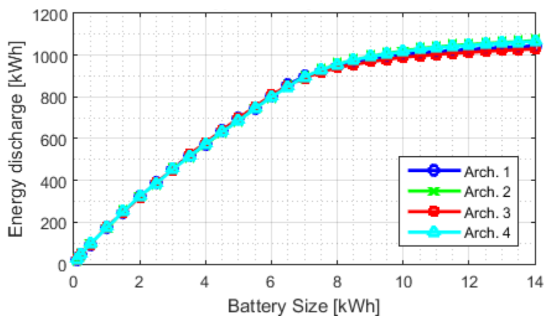

Figure 17. Energy discharge from battery

2) *AC-DC load proportion of 4th Architecture*

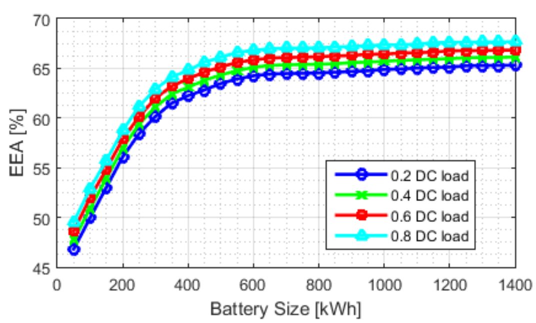

Figure 18. EEA base

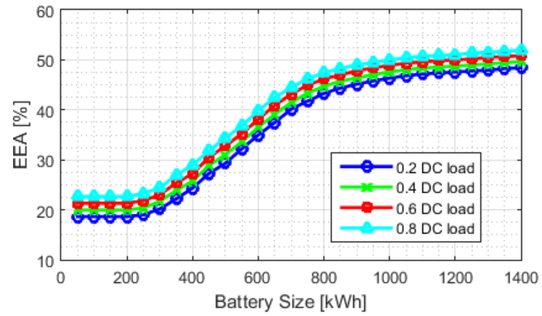

Figure 19. EEA off-peak

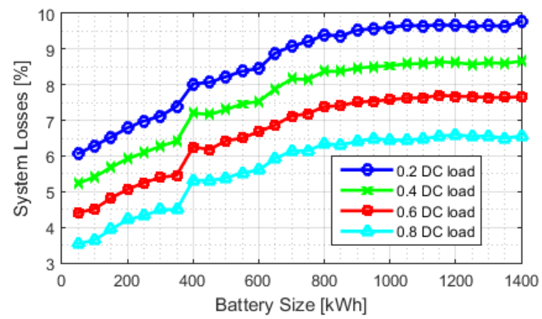

Figure 20. System losses

According to Fig. 18 - Fig. 20, the performance of the 4th architecture increases by increasing the proportion of dc load in the system. However, it requires a high portion of dc load to have better performance than the 3rd architecture. The 10% dc load is chosen as the parameter of the 4th architecture because currently households' load are in ac.