Transition towards Solar Photovoltaic Self-Consumption Policies with Batteries: From the Perspective of Distribution Networks

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***Abstract*— The transition towards low-carbon energy systems requires increasing the contribution of residential Photovoltaic (PV) in the energy consumption needs (i.e., PV self-consumption). For this purpose, the adoption of PV self-consumption policies as alternatives to the current net-metering policy may support harnessing batteries to improve PV self-consumption. However, the technical impacts of PV policies on distribution networks have to be adequately assessed and mitigated. To do so, a two-stage planning framework is proposed. The first stage is an optimization approach that determines the best sizes of PV and batteries based on the adopted PV policy. The second stage assesses the impacts of the resulting sizes on distribution networks using Monte-Carlo simulations to cope with uncertainties in demand and generation. The framework is applied on real medium and low voltage distribution networks from the south of Jordan. For the net-metering, the results show that the uptake of residential PV penetration above 40% will result in voltage issues. It is also found that the adoption of batteries for the benefits of customers (i.e., reduce electricity bills) will not mitigate the PV impacts for PV penetration above 60%. Further, the results demonstrate the important role of distribution network operators to manage the uptake of batteries for the benefits of customers and distribution networks. Network operators can support customers to adopt larger sizes of batteries to achieve the desired PV self-consumption in return of controlling the batteries to solve network issues. This facilitates the uptake of 100% PV penetration and improves PV self-consumption to 50%.**

***Index Terms*— batteries, distribution networks, net-metering, PV impacts, PV policies, PV self-consumption.**

I. Introduction

IN the last decade, governments worldwide formulated solar PV incentive policies to support the adoption of PV systems and provide positive business case for PV installations [1]. In particular, the net-metering policies adopted in different countries support residential customers with PV to reduce and even avoid the cost of energy consumption [2]. For instance, the net-metering policy in Jordan enables the transfer of excess PV generation as energy credit to compensate the cost of import energy within the day (e.g., night time periods) and throughout the netting period (e.g., three years) particularly during the winter season [3].

Although the net-metering policies encourage customers to install large PV capacity to increase exports and reduce electricity bills, the hosting capacity of distribution networks may be reached. In this respect, the uptake of PV systems and the opportunity to reduce electricity bills may be only limited to few network users with large energy consumption (i.e., non-fair PV access) [4]. Also, the net-metering policy will result in reduced revenues for network utilities. This requires increasing the electricity rates for non-PV owners to recover the costs of network operation and reinforcements [5].

Moreover, the net-metering policies may place barrier towards harnessing the technological advancements in residential batteries to improve the share of PV in the local energy consumption (i.e., PV self-consumption) through charging excess PV generation during the day to supply demand later. Taking into account the long netting period in the net-metering policies, power grid acts as virtual and large energy storage. This in turn will limit the feasibility of technical solutions to improve PV self-consumption levels [6].

As a result, the existing net-metering policy is expected to face a transition towards new policies that can both support fair PV access and enable the wide-scale adoption of batteries to increase PV self-consumption levels. In particular, this includes the transition towards PV self-consumption polices to encourage the local energy consumption from PV generation [7]. Different from the net-metering, the export energy in the PV self-consumption policies is remunerated at a much smaller rate than the import energy price [8]. This in turn may reduce PV exports and the PV impacts on distribution networks [9].

Future PV self-consumption policies may also enable Distribution Network Operators (DNOs) to lead the uptake of batteries and harness their capabilities to mitigate voltage and congestion issues at high PV penetration [10]. To do so, DNOs may partially participate in the capital cost of batteries in exchange of managing the batteries for both the benefits of distribution networks [11] and the provision of system services [12]. This in turn may improve the financial viability of batteries [13]. To inform policy makers, comprehensive frameworks are required to assess the implications of PV policies on both customers and distribution networks.

In the literature, most of the proposed models are carried out only from customers' perspective in terms of the return on PV and batteries investments. For instance, the effects of PV policies on the profitability for customers are assessed using the levelized cost of energy [14]. However, the assessment is carried out using single arbitrary load profile. In contrast, real residential load profiles are adopted based on measurements from a small group of customers [15] and from large dataset of smart-meter data [16]. Although Monte Carlo simulations are

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used to assess the impacts of net-metering [17] and PV self-consumption [18] on customers, the sizes of PV and batteries are predefined and assumed.

To determine the optimal sizes of PV and batteries, optimization-based models are presented in the literature. For example, a Mixed Integer Linear Programming (MILP) problem is adopted to define the optimal sizes under feed-in tariff (FiT) policy [19] and PV self-consumption policy [20]. Also, non-linear programming [21], exhaustive search method [22] and genetic algorithms [23] are all adopted to define the optimal sizes with net-metering and net-billing PV policies. Further, forecasting and estimation methods such as the wrapper-based feature selection approach [24], the machine learning method [25] and the random forest with feature selection approach [26] can be adapted to produce the optimal sizes. Nonetheless, none of the previous studies has considered the role of DNOs on the uptake of batteries. Further, none of these studies has assessed the implications on distribution networks.

To inform policy makers about future PV policies, the technical impacts on distribution networks have to be adequately assessed. The PV impacts on network voltages and congestions for different PV penetration are assessed using probabilistic power flows [27] to cope with the uncertainties in demand and generation. However, the impacts are limited to Low Voltage (LV) networks only. In contrast, the study in [28] considers both representative Medium Voltage (MV) and LV networks. However, the analysis is performed without batteries.

The impacts of PV coupled with batteries are assessed using deterministic [29] and probabilistic power flows [30]. However, batteries are managed for the benefits of customers to improve PV self-consumption. In this case, batteries are expected to be fully charged quickly before noon (critical periods) and PV impacts will likely still be seen on the networks. To ensure that there is adequate headroom in the batteries during critical periods to solve network issues, rules are adopted to delay the start time of charging [31] and restrict power exports below a defined limit [32]. However, these studies are considered from the perspective of distribution networks only. This in turn may affect the profitability for customers. Advanced management approach to cater for network issues whilst limiting the adverse effects on customers is proposed in [33]. However, the sizes of PV and batteries are defined arbitrarily and independent from PV policy. The same sizes are adopted for all the customers without considering their power and energy consumption needs. In addition, none of the aforementioned studies except from [28] has considered the role of PV policies. From modelling perspectives, none of the above studies except from [31] and [33] provide an integrated MV-LV distribution network modelling which is important to assess the impacts by capturing the power flows and voltages interactions between MV and LV.

Based on the above TABLE I provide a summary of the gaps in the literature. To properly address the challenges and bridge the gaps relative to previous work, this work presents a two-stage planning framework that aims to assess the role of PV policies on both residential customers and distribution networks. In particular, the framework aims to assess the extent at which the transition from the existing net-metering PV policy towards future PV self-consumption policies can support fairer PV access and improve PV self-consumption. The first stage of the framework is an optimization-based approach that determines the best sizes of PV and batteries for each customer based on the adopted PV policy. The resulting sizes are considered in the second stage to assess the impacts on distribution networks using Monte Carlo simulations per PV policy, per PV penetration and per desired PV self-consumption level. Further, the role of residential batteries in PV self-consumption policies is explored from sizing and control perspectives under two strategies. In the first strategy (user-led), batteries are managed by customers to improve PV self-consumption. In contrast, DNOs manage the uptake of batteries in the second strategy (DNOs-led) to support the adoption of larger sizes of batteries and harness their capabilities to solve network issues at high PV penetration with the minimal impacts on customers. The framework is demonstrated on real integrated MV-LV distribution network from the south of Jordan considering real hourly PV and load profiles.

The main original contributions of this work can be summarized as follows:

- A novel and comprehensive two-stage planning framework is proposed to assess the implications of departing from the net-metering policy to the PV self-consumption policy with batteries from both the perspective of distribution networks, as well as from customers' point of view. The framework enables defining the maximum PV penetration and PV self-consumption level per each PV policy whilst respecting the technical constraints of distribution networks.
- A general MILP optimization approach is formulated to determine the sizes of PV and batteries based on PV policy and considering strategies when DNOs manage the uptake of batteries.
- An innovative management approach is proposed to harness the capabilities of batteries to effectively mitigate the PV impacts on distribution networks with minimal effects on customers.
- A thorough assessment is established to evaluate the impacts of PV policies on network voltages and congestions considering real time-series data and using Monte Carlo simulations to cope with uncertainties.
- A comprehensive comparison between the user-led and DNOs-led strategies is carried out to understand the potential role of DNOs to manage the uptake of batteries in the PV self-consumption policy.
- A real MV-LV integrated distribution network model is developed to capture the voltage interactions between MV and LV networks so that the impacts of each PV policy on distribution networks could be adequately assessed.

The rest of this paper is structured as follows: Section II provides an overview of net-metering and PV self-consumption policies. The two-stage planning framework is presented in Section III. The formulation to model the planning framework is provided in Section IV. In sections V and VI, the results from the application of the proposed framework on a real MV-LV distribution network are presented and discussed. Section VII discusses future research to be undertaken. Finally, conclusions are drawn in section VIII.

II. Overview of PV Policies

This section provides a detailed overview of the net-metering and PV self-consumption policies.

TABLE I. Comparisons of different studies in the literature

Features		Studies in the literature									This work
		[14-18]	[19-23]	[24-26]	[27]	[28]	[29]	[30]	[32]	[31], [33]	
Impacts of PV policies on	customers	Yes	Yes	No	No	Yes	No				Yes
	distribution networks	No	No	No	No	Yes	No				Yes
Optimal sizes of PV and batteries	Method to define the optimal sizes	No (sizes are assumed)	Yes (MILP, NLP, exhaustive search and Genetic)	No (forecasting methods can be adapted to produce the optimal sizes)	No (sizes are assumed)						Yes MILP
	customers perspective		Yes								Yes
	DNOs perspective		No								Yes
Impacts on distribution networks	Caters for uncertainty	-	-	-	Yes		No	Yes	No	Yes	Yes
	Integrated MV – LV	-	-	-	LV	MV and LV	LV	MV	LV	Yes	Yes
Control batteries for the benefits of	customers	Yes	Yes	-	No	No	Yes	Yes	No	Yes	Yes
	DNOs	No	No	-	No	No	No	No	Yes	Yes	Yes

A. Net-metering PV Policy

To illustrate the mechanism of net-metering, Fig. 1 presents an example of PV generation profile (dashed line) and demand profile (solid line) during a summer day. It can be seen that the customer's power consumption needs can be fed from PV only for part of the daylights time period between T_2 and T_3 without the need to import power from grid. However, the grid is still necessary when the PV power generation becomes smaller than demand. For instance, power is imported from the grid between T_1 and T_2 (in the morning) and between T_3 and T_4 (in the afternoon) to cover the deficit power. The grid also enables exporting of surplus generation when power generation exceeds demand between T_2 and T_3.

To enable compensating the cost of import energy particularly during night and evening time periods (shaded areas C_1 and C_2), the total export energy (in the area B) is remunerated under the net-metering at the same rate as the import energy price. Therefore, the final electricity bill for this day can be either reduced significantly or even reach to zero. The reduction in the electricity bills is also possible during winter seasons albeit the low-PV energy production. This is because that the net-metering allows the transfer of excess energy at an electricity bill (i.e., export energy is larger than import energy) as energy credits to offset energy consumptions in the subsequent bills and throughout the netting period (it can be extended to several years).

The rewards given to the export energy and the rapid cost reduction in PV encourage customers to adopt larger PV sizes to increase exports to the grid, thus reducing electricity bills. Although it seems that the net-metering encourages PV uptake, it may not ensure fair PV access to all the network users. This is since the hosting capacity of the distribution networks may be violated with just few large-scale PV installations from customers with relatively high energy consumption needs.

Due to the grid constraints, it might not be possible for small customers to install PV and have access to the net-metering incentives. It is also worth to highlight that the adopted net-metering in some countries enables customers with PV to reduce the electricity bills to zero even without paying the cost of grid usage to exchange power and particularly when network reinforcements are conducted due to excess PV generation.

B. PV Self-Consumption Policy

To mitigate challenges raised by the net-metering, it is important to move towards alternative PV policies to enable the

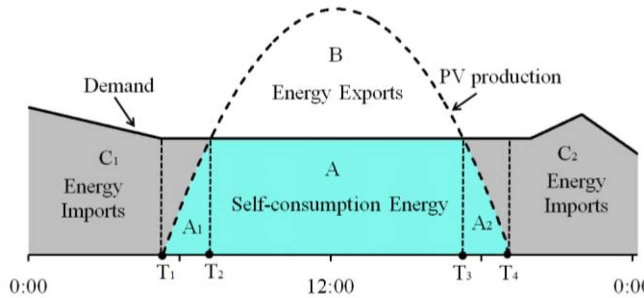

Fig. 1. Example of residential demand and PV generation pofiles.

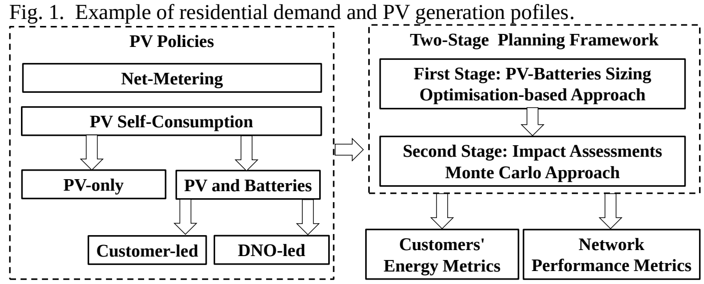

Fig. 2. Structure of the two-stage planning framework

wide-scale adoption of PV in a fairer manner whilst ensuring better local utilization of PV and reducing PV exports to the grid. Under the PV self-consumption, the export energy is remunerated at a much smaller rate compared to the import energy price. This change may in turn promote local energy consumption of PV generation and thus reducing PV exports. Further, this may result in smaller PV sizes and better utilization of the hosting capacity of distribution networks to serve more customers with PV.

The design of PV self-consumption may also consider removing any form of rewards to the export energy so that the reduction in the electricity bills is only defined in proportion to the share of the energy consumption needs that is instantaneously supplied from PV (i.e., electricity bill is defined only based on the import energy). For instance, the reduction in the electricity bill is only based on the volume of energy consumption that could be either fully (shaded area A in Fig. 1) or partially supplied by PV (shaded areas A_1 and A_2 in Fig. 1). From customers' perspective, this policy might be also seen economically feasible due to the expected rapid drop in PV cost and the increase in the retail energy price.

Battery energy storage systems are also one of the key solutions that could be adopted by customers with PV to improve the local consumption of self-produced energy and thus reducing electricity bills. Batteries enable charging excess generation throughout the day to supply demand particularly during evening and night periods. However, the impacts of batteries on distribution networks should be better explored. In particular, it is important to understand the necessity to introduce new rules or alternative ownership models that would enable harnessing the capabilities of batteries to solve distribution network issues.

III. Two-Stage Planning Framework

To inform policy makers about the required amendment in the existing PV policies, advanced planning models are required to understand the extent at which existing and future PV policies can increase PV penetration and improve PV self-consumption level whilst respecting thermal and voltage constraints of distribution networks. The structure of the two-stage planning framework to assess the impacts of both the net-metering and PV self-consumption policies is presented in Fig. 2.

The *first stage* of the planning framework is an optimization-based approach that aims to determine the minimum sizes of PV and battery at a residential house to achieve a desired reduction in the electricity bill based on the customers' consumption needs and the adopted PV policy. The definition of the best sizes enables assessing the impacts of PV policies on distribution networks adequately without over/under estimation.

For the net-metering policy, the best PV size is the one that can result in a sufficient volume of export energy across the netting period to reduce the net-amount of energy (import energy minus export energy) and achieve the desired bill reduction. In contrast, the PV self-consumption policies adopted in this work determines the reduction in the electricity bill based on the share of energy consumption that is supplied from PV either directly or by the adoption of batteries (i.e., PV self-consumption level). In this respect, the sizes of PV and batteries are found to achieve a desired PV-self consumption level as a proxy of bill reduction.

The *second stage* of the planning framework aims to assess the technical impacts of PV polices on distribution networks based on the sizes of PV and batteries found in the *first stage*. The impacts are found in terms of the violations of network voltages and thermal limits. Further, uncertainties related to load and generation and PV locations are catered for via *Monte Carlo* simulations carried out per PV policies, per PV penetration and per PV self-consumption level.

To adequately understand the implications of the wide-spread adoption of batteries, the planning framework will also explore the role of batteries in the PV self-consumption policies under two strategies. In the first strategy, the adoption of batteries is led by customers (*user-led*) to achieve a desired PV-self consumption level. In contrast, the uptake of batteries in the second strategy is led by distribution network operators (*DNO-led*) to manage network constraints with minimal impacts on the customers' desired PV self-consumption level. The details of the two strategies are presented in the next sections.

A. User-Led Batteries Sizing and Control Strategy

In this strategy, the sizes of PV and batteries are determined from customers' perspective to minimize the installation cost whilst achieving the desired PV self-consumption. Considering

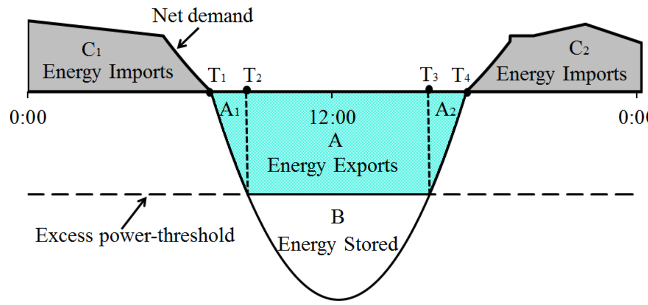

Fig. 3. A residential net demand profile with PV.

that the unit cost of PV is cheaper than battery, the objective function in the first stage is formulated to achieve the desired PV self-consumption using larger PV sizes and with the minimum required sizes of batteries.

In the second stage, the management of batteries is also carried out for the benefits of customers to harvest as much as possible of excess PV generation to supply local demand later. To do so, charging is directly enabled once PV generation exceeds the local demand. The charging process continues until the battery reaches its energy capacity. Hereafter, excess PV generation is exported to the grid. To reduce import energy and achieve the desired self-consumption level, the stored energy is discharged during evening and night time periods to supply local demand.

It is important to highlight that the *user-led* strategy may not effectively mitigate the PV impacts on distribution networks. This is due to the adoption of small sizes of batteries. Also, the charging approach may lead to the batteries quickly fully charged before the critical time periods (e.g., noon).

B. DNO-Led Batteries Sizing and Control Strategy

In this strategy, distribution network operators contribute in the investment in batteries to achieve the desired PV self-consumption. This in turn may reduce excess PV generation and enable higher PV penetration without the violation of network constraints.

In return of DNOs' contributions in the investment in batteries, alternative charging operation of batteries is adopted in the second stage -when it is necessary- at high PV penetration to effectively mitigate the PV impacts. Different from the previous strategy, the charging operation of batteries in the second stage is modified to limit the charging periods when excess PV generation exceeds a predefined power threshold. The charged power is also determined to maintain the excess PV generation below the defined *excess-power threshold*. For instance, charging is only allowed between T_2 and T_3 for the net demand given in Fig. 3. These constraints on charging may in turn delay the time periods when the batteries become fully charged and provide adequate head room during critical time periods (e.g., around noon) to charge excess generation and mitigate the PV impacts. To ensure fairness between customers with different PV power ratings, the *excess-power threshold* is defined as a percentage of PV rating.

The most adequate *excess-power threshold* could be defined after assessing the impacts of different values on both customers' PV self-consumption and distribution networks. The adoption of small values of *excess-power threshold* (e.g., zero) will force the battery to charge as much as possible of the available excess PV generation like the *Customer-Led Strategy*.

In contrast, the adoption of large values of *excess-power threshold* (close to unity) will not necessarily solve network issues since this will enable the delivery of large values of excess PV generation to the grid. Further, large values of *excess-power threshold* may reduce the stored energy and increase import from grid in the evening and night periods (i.e., not achieving the desired PV-self consumption level).

IV. Problem Formulation

This section presents the formulation of the two-stage planning framework. The first stage aims to determine the best sizes of PV and battery per each residential customer in response to the adopted PV policy. The second stage assesses the impacts on distribution networks based on the sizes found in the first stage. The modelling of both stages enables the provision of comprehensive impact assessments of PV policies on both customers and distribution networks compared to previous studies.

A. First-stage: PV - Batteries Sizing

The formulations proposed in the authors' previous work in [12] in the context of residential community energy management system with PV and batteries have been adopted to model the batteries and the net-demand of customers. Further, new formulations have been considered to decide the optimal sizes. For completeness, this Section presents the full formulations classified based on the PV policies (net-metering and PV self-consumption) and the strategies to manage the uptake of batteries (user-led and DNO-led).

1) Net-metering PV policy

With this policy, the grid acts as virtual energy storage because import and export energy are both remunerated at the same rate. Therefore, batteries are not considered under this policy. The objective function is formulated in (1) to minimize the size of PV system P^{PV} (*kW*) to achieve a desired reduction in the electricity bill.

$$min\ P^{PV} \tag{1}$$

The bill with PV C_{PV}^{bill} is calculated based on the net amount of import energy E_{PV}^{import} (*kWh*) and export energy E_{PV}^{export} (*kWh*) throughout the netting period T^{net}, as given in (2). The desired bill reduction is expressed as percentage (α) of the bill without PV as in (3).

$$C_{PV}^{bill} = \left(E_{PV}^{import} - E_{PV}^{export}\right)\pi \tag{2}$$

$$C_{PV}^{bill} \leq (1-\alpha)\,\pi \sum_{t\in T}^{T^{net}} p_t^{load} \tag{3}$$

where p_t^{load} is the customer's power consumption at each time step (set T indexed by t). It is also worth to highlight that the applied electricity rate π (e.g., *cent/kWh*) is the same for both the import and export energy. Therefore, its value will not affect the optimal PV size.

To determine the import and export energy across the netting period, the import and export power at each time step have to be defined. To do so, the excess PV generation p_t^{excess} at each time step is found using the balance equation in (4) and it is modelled using two non-negative variables $\left(p_t^{\text{import}}, p_t^{\text{export}}\right)$ to represent import and export power, respectively as given in (5).

$$p_t^{excess} = P^{PV}\Gamma_t - p_t^{load};\ \forall\, t \tag{4}$$

$$p_t^{excess} = p_t^{\text{export}} - p_t^{\text{import}};\ \forall\, t \tag{5}$$

where Γ_t is the normalized PV power profile.

To ensure that importing and exporting will not occur simultaneously, a binary variable is used to determine the status of the house, x_t (e.g., $x_t = 1$ means that the house imports power from the grid). This in turn makes the formulation as a Mixed Integer Linear Programming (MILP).

$$0 \leq p_t^{\text{import}} \leq x_t\, M;\ \forall\, t \tag{6}$$

$$0 \leq p_t^{\text{export}} \leq (1-x_t)\, M;\ \forall\, t \tag{7}$$

where M is a large number selected to satisfy power needs of the house.

2) PV self-consumption policy

With this policy, the objective function is formulated in (8) to minimize both the PV rating P^{PV} and the battery energy capacity $E^{battery}$ as a proxy of the capital cost of the system. For this policy, the bill is defined only based on the import energy. To achieve the desired reduction in the electricity bill, part of the customer's energy consumption has to be supplied from PV to reduce the import energy. For this purpose, the constraint in (9) is formulated to impose constraint on the import energy based on the desired PV self-consumption level $\lambda^{desired}$.

$$min\ w_{PV}\, P^{PV} + w_{battery}\, E^{battery} \tag{8}$$

$$E_{PV}^{import} \leq (1-\lambda^{desired}) \sum_{t\in T} p_t^{load} \tag{9}$$

Both the sizes of PV and battery are related in a single equation in the objective function using the weighting coefficients (w_{PV} and $w_{battery}$) whose values are selected based on the adopted battery sizing strategy. In the *user-led strategy*, the sizes are found from customers' perspective to minimize the overall capital cost of the system. To do so, the weighting coefficients correspond to the relative costs of the PV rating and the battery energy capacity. Considering the current unit costs of PV and batteries ($w_{PV} < w_{battery}$), customers will adopt larger PV sizes to achieve the desired self-consumption level and with the minimum required size of batteries. In the *DNO-led strategy*, the desired PV self-consumption level is obtained with smaller PV size and larger size of batteries to reduce both the excess PV generation and the impacts on distribution networks. Therefore, the unit cost of PV is adopted larger than the unit cost of battery ($w_{PV} > w_{battery}$) considering the compensation of DNOs in the cost of battery,

The battery is controlled subject to set of constraints in (10-12). The battery is controlled to discharge (p_t^{dis}) or charge (p_t^{ch}) active power, at each time step within the battery power rating, $P^{\,battery}$. The difference between the discharge and the charge power defines the output power of the battery (positive values of $p_t^{battery}$ correspond to injection of power, i.e., discharging).

$$0 \leq p_t^{dis} \leq P^{\,battery};\ \forall\, t \tag{10}$$

$$0 \leq p_t^{ch} \leq P^{\,battery};\ \forall\, t \tag{11}$$

$$P^{\,battery} = p_t^{dis} - p_t^{ch};\ \forall\, t \tag{12}$$

To ensure that charging and discharging actions of a battery are not applied simultaneously, the status of each battery is defined as a binary variable z_t (e.g., $z_t = 1$ means that the battery is in the discharging mode). The status of battery is formulated in (13) and (14).

$$0 \le p_t^{dis} \le z_t \times P^{battery};\ \forall t \quad (13)$$

$$0 \le p_t^{ch} \le (1 - z_t) \times P^{battery}\ ;\ \forall t \quad (14)$$

The model is also subject to a set of constraints that cater for energy ratings as well as the inter-temporal constraints of batteries throughout the planning horizon. The energy losses that result from energy and power conversion have to be accounted for during charging and discharging. Therefore, the change in the stored energy, ΔE_t^{stor} , at each time step and the corresponding stored energy, E_t^{stor}, can be represented by (15) and (16), respectively.

$$\Delta E_t^{stor} = \left(\frac{p_t^{dis}}{\eta^{dis}} - p_t^{ch} \times \eta^{ch}\right) \times \Delta t \quad \forall t \quad (15)$$

$$E_t^{stor} = E^{(0)} - \sum_{t=1}^{t=N} \Delta E_t^{stor} \quad \forall t \quad (16)$$

where η^{ch} and η^{dis} are the charging and discharging efficiencies, respectively. $E^{(0)}$ is the initial stored energy at the beginning of the planning horizon, Δt is the time step and the planning horizon is divided into *N time steps*.

To preserve the lifetime of battery, the stored energy can be kept above a particular minimum stored energy level E^{min}. Therefore, the stored energy is controlled between a minimum level and its rated capacity ($E^{battery}$).

$$E^{min} \le \quad E_t^{stor} \le E^{battery}\ ;\ \forall t \quad (17)$$

To determine the PV self-consumption level, the import energy has to be defined. To do so, the excess PV generation p_t^{excess} at each time step is found using the power balance equation in (18) and it is modelled using two nonnegative $\left(p_t^{\text{import}}, p_t^{\text{export}}\right)$ to represent import and export power, respectively, as formulated in (5) – (7).

$$p_t^{excess} = P^{PV}\Gamma_t + p_t^{battery} - p_t^{load};\ \forall t \quad (18)$$

B. Stage 2: Impact Assessments on Distribution Networks

The impact assessment methodology presented in [31] is adapted to understand the technical impacts of each PV policy on distribution networks. To cater for PV growth, five PV penetration levels are adopted. The penetration of PV refers to the percentage of residential customers with PV systems (e.g., 60% penetration level means that 60% of the houses have PV systems). The penetration level is increased in steps of 20% until each residential customer has a PV system (i.e., 100% penetration). For each customer with PV, the sizes of PV and batteries are determined from the first stage.

The management of batteries is carried out based on the batteries control strategy (as explained in Section III). In the *user-led* strategy, charging is enabled during periods of excess PV generation. Like the control implemented in the first stage, the battery is controlled to charge the available excess PV generation as given in (19).

$$p_t^{ch} = P^{PV}\Gamma_t - p_t^{load} \quad (19)$$

In the *DNO-led* strategy, a power threshold is defined per customer to determine periods of charging and the charged power. Charging is only allowed when the excess PV generation exceeds the defined power threshold. This threshold is expressed as a percentage of the customer's PV rating. The same percentage $\varepsilon^{threshold}$ is adopted for all the customers in the network. The charged power at each time step is given in (20) to maintain the excess PV generation below the defined threshold.

$$p_t^{ch} = P^{PV}\Gamma_t - p_t^{load} - \varepsilon^{threshold}P^{PV} \quad (20)$$

For both strategies, charging continues until the stored energy reaches the energy capacity of the battery.

To cater for the uncertainties in demand and generation, Monte Carlo simulations are carried out per PV penetration level. Multiple scenarios of PV locations and load profiles are considered. To determine the maximum possible PV self-consumption level without the violation of network constraints, the impacts are also assessed for multiple desired PV self-consumption levels.

V. Real Jordanian MV– LV Network Modelling

The net-metering PV policy has been implemented in Jordan from 2012 to support PV installations. However, DNOs adopt conservative connection rules at LV networks to mitigate the PV impacts. These rules have placed barriers to enable residential PV penetration. Therefore, it is important to assess the technical impacts of the net-metering policy on the Jordanian distribution networks to adequately define the PV hosting capacity. Further, the Jordanian energy strategy aims to increase the proportion of PV in the total energy consumption. However, the current net-metering policy supports PV exports to the grid to reduce the electricity bills. This places barriers towards the adoption of batteries. Therefore, alternative PV policies beyond the net-metering are needed to improve self-consumption. The proposed framework will provide the energy policy makers in Jordan with better understanding of the extent at which the transition from the current net-metering towards future PV self-consumption policy can both increase residential PV penetration and improve PV self-consumption without the violation of distribution network constraints.

To assess the implications of PV policies on distribution networks, models for both MV and LV networks are required. For this purpose, a real MV (33 kV) network from the south of Jordan operated by the Electricity Distribution Company (EDCO), was modelled. To apply the proposed framework, the network data is converted from EDCO's power system analysis software (CYMDIST by CYME) [34] to the distribution network analysis software package OpenDSS [35].

The corresponding single line diagram is shown in Fig. 4. The feeder is mostly constituted by overhead lines (94%) with a cross section of 100 mm^2 and for a total length of about 70 km. The feeder also accommodates PV systems connected at a distance of 23 km from the beginning of the feeder and with capacities of 4.4 MW. The feeder supplies power to 82 distribution transformers (33/0.415 kV) with capacities ranging between 25 and 1,000 kVA. All the transformers are within a distance of 35 km from the head of the MV feeder. Most of the distribution transformers (65%) are private and dedicated for big customers (e.g., private large commercial activities). The loads of private transformers are modelled as spot loads and they are directly connected to the LV busbar of the transformer without the detailed modelling of LV networks. The rest of distribution transformers are public (35%) and they supply power to residential and non-residential customers.

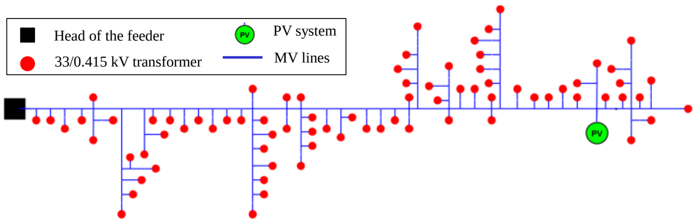

Fig. 4. Real 33kV network from the south of Jordan with an exisiting PV plant of 4.4 MW.

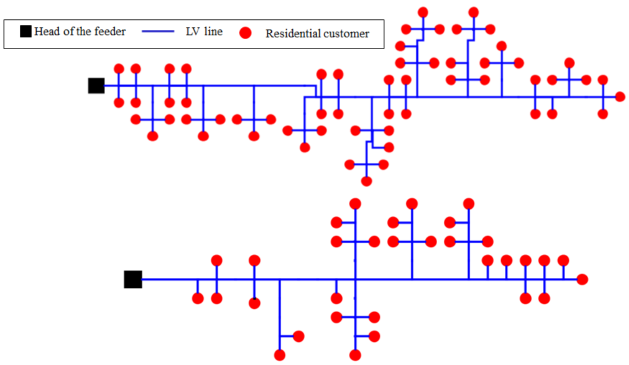

Fig. 5. Examples of residential low voltage feeders from the south of Jordan.

The following process is carried out to model the LV networks of public transformers based on the available data. The LV networks are assigned to the transformers from a set of representative residential LV feeders that are adopted by EDCO for planning purposes. The assignment of the representative LV feeders is carried out on the basis of both the rated power and the loadings of transformers. Fig. 5 shows examples of the representative LV feeders. Each LV feeder has unique features in terms of lengths and types of LV lines and number of supplied customers. The number of customers connected along the representative residential LV feeders is between 30 and 67. The farthest customer to the head of the LV feeder is in the range between 450 meters and 1400 meters for all the feeders. The public distribution transformers also accommodate small non-residential customers. For simplicity, they are modelled as spot loads and connected to the LV busbar of the transformer.

The load profiles of residential customers are produced based on a pool of residential power measurements with 10-min resolution and for one week that are taken during different periods in the year. Further, the load profiles of non-residential customers connected to public and private transformers are defined to match both the real power measurements available at the beginning of the MV feeder and the yearly energy consumption measured at each distribution transformer. To model the annual variations of PV generation profiles, hourly normalized PV generation profiles for one year are adopted from a site in Jordan.

The available hourly power measurements at the head of the MV feeder for one year are also analysed to determine the minimum, average and maximum power of the feeder at each time step in the day (24 hours). The results are presented in Fig. 6. It can be noticed that the minimum demand of the feeder is 2.8 MW and it occurs during the middle of the day in summer (coincident with the high production of the MV-connected PV). Also, the peak demand of the feeder is 8.6 MW that occurs in winter during night periods.

To enable the delivery of voltages within their statutory limits (±10%) during all the loading conditions, it is also important to determine the best tap position of distribution transformers (33/0.415 kV) that are equipped with off-load tap changer whose capability range is ±5% (5 tap positions, 2.5% per step). Considering that the distribution transformer provides 3.75% voltage boost above the nominal voltage of 230 V at the nominal tap position, the best tap position is set to provide voltage gain on customers, the sizes of PV and batteries are predefined and assumed.

It is important to highlight that the voltage ratio of distribution transformers (33/0.415 kV) and the adopted tap position will result in an overall voltage boost of 6.25% above the nominal voltage of 230 V. This in turn will reduce the hosting capacity of the analysed distribution network to connect residential PV with high penetration. The MV-connected PV systems can also increase the voltages received at the high voltage side of distribution transformers resulting in further reduction in the hosting capacity.

For illustration purposes, Fig. 7 shows the LV busbar (line to neutral) voltage profiles of all the distribution transformers for a day in summer with high PV production. The voltages are presented using boxplots. It can be noticed that the voltage variations from early morning to late evening due to demand and generation variability are around 16 V (between 228 V to 244 V). The highest LV busbar voltage reaches 244 V, which is only smaller than the upper limit (253 V) by 9 V. This shows the limited hosting capacity of the analysed network and the importance of integrated MV-LV models to capture voltage interactions compared to only modelling LV networks with a fixed busbar voltage of 1 p.u. (230 V).

VI. Results

The two-stage planning framework is applied to the real MV-LV distribution network from the south of Jordan. The optimization problem at the first stage to determine the optimal sizes of PV and batteries is formulated using the optimization modelling software AIMMS [36]. The objective functions and the constraints of the optimization problem are all linear. The problem also includes binary decision variables related to the status of battery z_t, (charging or discharging mode) and the net-demand status of the house x_t, (import or export). Thus, the resulting formulation is a Mixed Integer Linear Programming (MILP) model and it is solved using the CPLEX solver [37]. The distribution network analysis software package OpenDSS [35] is adopted at the second stage to perform time-series and three-phase unbalanced power flows considering 1-hour resolution (24 time steps in a day) to assess the PV impacts on distribution networks. The impacts are found in terms of congestions and voltage issues. Based on the distribution performance standard in Jordan [38], the voltage limits are ±10% for LV customers (nominal voltage 230 V line-to-neutral). The results for each PV policy are presented in the next sections.

A. *Net-metering PV Policy*

This section presents the PV impacts under the net-metering policy on the analysed MV-LV distribution network. The sizes of residential PV systems are found in the first stage of the planning framework to reduce electricity bills to zero ($\alpha = 1$ in (3)). For illustration purposes, the total residential PV capacity

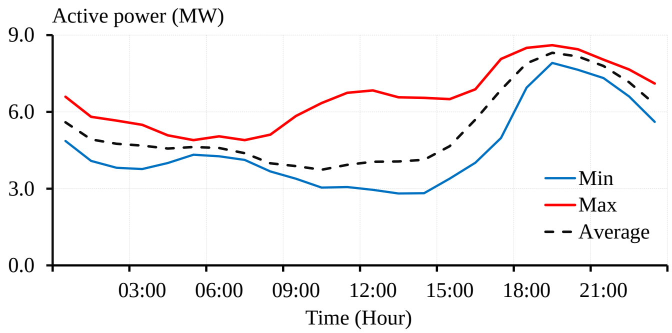

Fig. 6. The minimum, average and maximum active power at each time step measured at the head of the MV feeder.

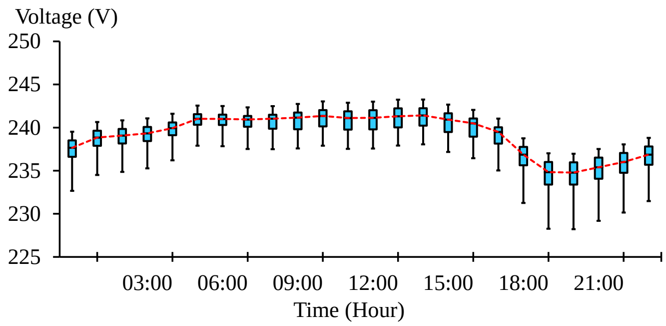

Fig. 7. LV busbar line to neutral voltages in a summer day. The bottom of the box is the 25th percentile of the transformers. The top of the box is the 75th percentile of the transformers. The dased red line inside the box is the median (50th percentile of the transformers).

at each of the five PV penetration levels is presented in TABLE II. The resulting total PV installed capacity of both the residential PV and the MV-connected PV (4.4 MW) ranges from a relatively small value of 5.8 MW (68% of the total peak demand) to 11.4 MW (130% the total peak demand). The PV impacts are assessed in terms of the loading of network assets. It is found that residential PV does not present congestion issues in network assets. The loading levels of LV lines, distribution transformers and MV lines are within their thermal limits for all the simulations at each penetration level.

However, the growth of residential PV penetration will significantly modify the power profiles seen at the head of the MV feeder. For illustration purposes, the minimum, average and maximum power flows at each time step in the day (24 hours) are obtained from the daily power flows carried out throughout the year at 100% residential PV penetration. The resulting daily power profiles are presented in Fig. 8. It can be noticed that the minimum and the average power are reduced significantly in the middle of the day compared to their values without residential PV (Fig. 6). In particular, reverse power flows to the upstream network voltage level can occur for 19% of the year and with an absolute magnitude of 2.6 MW. In contrast, the average power during evening and night periods has not been affected with PV. This highlights the potential to effectively utilize excess PV generation locally to reduce energy consumption needs.

The PV impacts are also assessed in terms of the maximum voltages across residential customers and the loading of network assets using Monte Carlo analysis. Fig. 9 shows the LV busbar voltage profiles of all the distribution transformers for a day in summer with high PV production and considering 100% residential PV penetration. The voltage results are presented using boxplots. It can be noticed that the median of LV busbar voltages in the middle of the day are increased to 245 V from

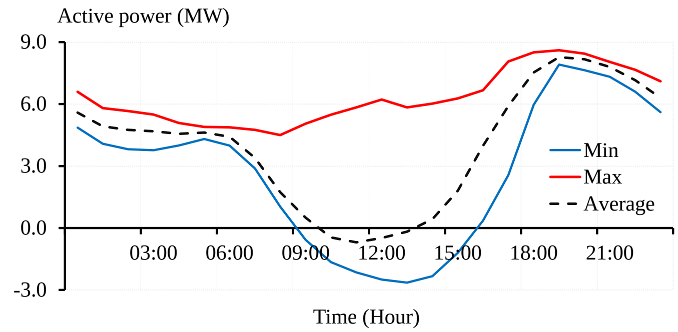

Fig. 8. Net-metering policy at 100% PV penetration: The minimum, average and maximum active power at each time step at the head of the MV feeder.

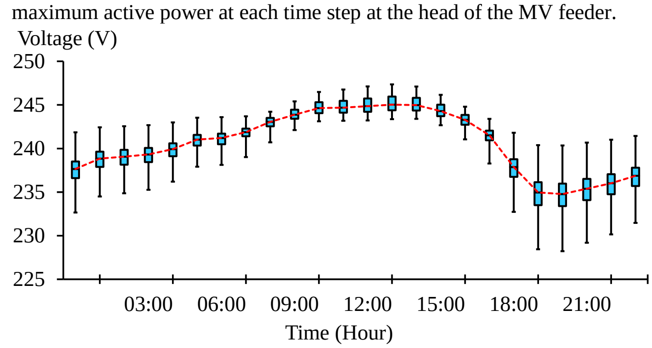

Fig. 9. Net-metering at 100% PV penetration: LV busbar line to neutral voltages in a summer day. The bottom of the box is the 25th percentile of the transformers. The top of the box is the 75th percentile of the transformers. The dased red line inside the box is the median (50th percentile of the transformers).

241 V without PV (as can be noticed in Fig. 7). The increase in the LV busbar voltages will limit the maximum residential PV penetration at LV feeders. This can be seen in Fig. 10 which presents the maximum voltages across residential customers for all the simulations using boxplots. The bottom of the box is the 25th percentile of the simulations. The top of the box is the 75th percentile of the simulations. The bold line inside the box is the median (50th percentile of the simulations). It can be noticed that the first PV penetration resulting in voltages above the upper limit is at a PV penetration of 60% with 17% of the simulations are exceeding 1.1 p.u.. The frequency and magnitude of voltage issues increase significantly at higher PV penetrations. For example, the median of the maximum voltage at 100% residential PV penetration is 1.13 p.u.

B. PV Self-Consumption Policy – PV Only

This section aims to understand the extent to which the PV-self consumption policy can increase PV penetration compared to the net-metering policy so that more residential customers can have access to PV without the violation of network constraints. Here, the optimal PV sizes are found in the planning framework to achieve a desired PV self-consumption level λ (share of customer's energy consumption needs fed instantaneously from PV). Three PV self-consumption levels are adopted; 10%, 20% and 30%. Different from the net-metering, it will not be possible for customers with PV to reduce electricity bills to zero. Thus, smaller PV size per residential customer is expected compared to the net-metering.

TABLE III provides the total residential PV capacity for each of the analysed PV self-consumption level at 100% residential PV penetration. The results show that the maximum voltages across residential customers will not exceed the upper limit for all the simulations and the analysed PV self-consumption levels.

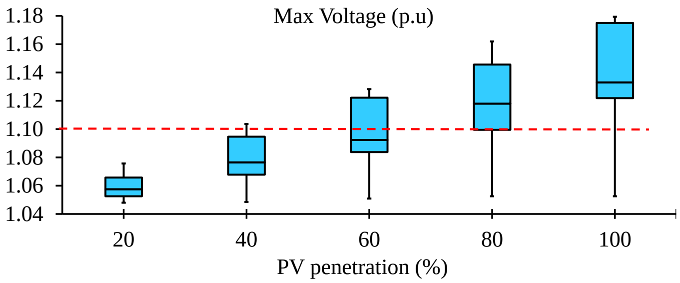

Fig. 10. Net-metering policy: impact assessment of PV on voltages using boxplots. The dashed red line is the voltage limit. The red line is the maximum voltage limit (1.1 p.u.).

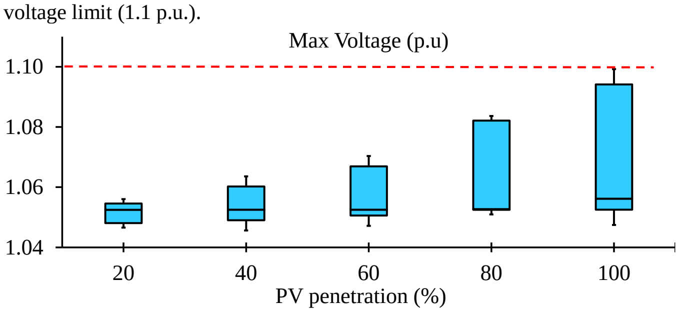

Fig. 11. 30% PV self-consumption policy: impact assessment of PV on voltages using boxplots. The dashed red line is the voltage limit. The red line is the maximum voltage limit (1.1 p.u.).

TABLE II. Net metering policy: PV capacity at different PV penetration

PV Penetration level	20%	40%	60%	80%	100%
PV capacity (MW)	1.36	2.7	4.1	5.4	6.9

TABLE III. PV Self-consumption policy at 100% PV penetration: PV capacity at different PV self-consumption levels

PV Self-Consumption level	10%	20%	30%
PV capacity (MW)	0.8	1.6	2.8

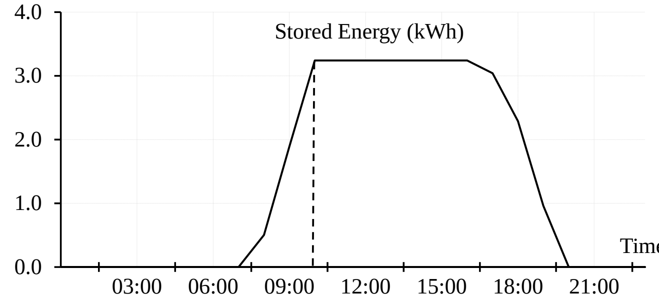

Fig. 12. *User-led* strategy at 40% desired PV self-consumption level: Stored energy profile for a 3.2 kWh battery in a summer day

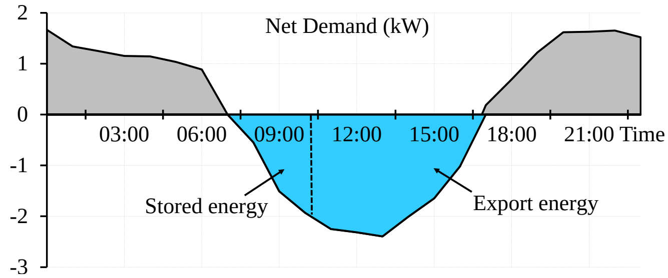

Fig. 13. *User-led* strategy at 40% desired PV self-consumption level: Net demand profile for a residential customer with in a summer day.

TABLE IV. User-led battery strategy: PV and batteries capacities at 40% and 50% PV self-consumption levels

PV Self-Consumption level	40%	50%
PV capacity (MW)	4.4	7.2
Batteries capacity (MWh)	1.2	4.5

TABLE V. DNO-led battery strategy: PV and batteries capacities at 40% and 50% PV self-consumption levels

PV Self-Consumption level	40%	50%
PV (MW)	3.8	4.6
Batteries (MWh)	2.4	6.8

Further, the assessment of PV impacts for different residential PV penetration shows that it is possible to achieve a 100% residential PV penetration.

For demonstration purposes, the voltage results at 30% PV self-consumption are presented in Fig. 11. It can be noticed that the residential PV capacity at 100% PV penetration level (2.8 MW) equals to the maximum capacity that can be achieved in the net-metering without voltage issues (i.e., 40% PV penetration level). Thus, it can be concluded that the hosting capacity of distribution networks could be better utilized in the PV self-consumption policies to support a larger number of residential PV installations than in the net-metering. Therefore, this policy supports fairer PV access than the net-metering policy.

C. PV-Self Consumption with Batteries: User-Led Strategy

In this case, the installation of PV is coupled with residential batteries to improve PV self-consumption. The sizes of PV and batteries are determined in the *user-led* strategy to minimize the installation cost whilst achieving the desired self-consumption. This is considered in equation (8) by setting the unit cost of battery per kWh to be three times that of the PV rating (in kW), i.e., w_{PV}= 0.25 unit cost per kW and w_{bat}= 0.75 unit cost per kWh. 40% and 50% desired PV self-consumption levels are adopted. The overall resulting sizes at 100% residential PV penetration are presented in TABLE IV. The analysis shows that 86% of the residential customers can achieve a 40% PV self-consumption without the need to batteries. However, batteries are required at all the residential customers at 50% PV self-consumption.

To illustrate the management of batteries in the *user-led* strategy, Fig. 12 shows the stored energy profile for a residential customer with PV size of 3.6 kW and battery with energy capacity of 3.4 kWh for a day in summer. For this day, the net demand profile of the customer with PV only (demand minus PV generation) is also presented in Fig. 13 to better describe the charging and discharging actions of the battery. It can be seen that from 08:00 to 16:00, the battery is required to harvest as much as possible of excess PV generation to supply local demand later. This charging process lasts until the stored energy reaches the energy capacity of the battery at 10:00. After this time, excess PV generation will be exported to the grid which may result in the violation of network constraints. From 17:00 to 20:00, the stored energy is used to supply the local demand to reduce the import energy and achieve the desired PV self-consumption level. The discharging process continues until the battery becomes fully discharged. Hereafter, the battery goes into idling mode.

To understand the implications of the sizes of PV and batteries found in the *user-led* strategy on distribution networks, Fig. 14 presents the maximum voltage across residential customers for all the simulations using boxplots considering 40% PV self-consumption level. It can be noticed that the impacts of residential PV will still be seen on the networks

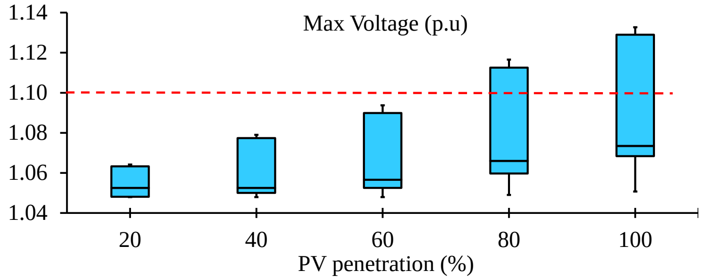

Fig. 14. *User-led* battery strategy at 40% desired PV self-consumption level: impacts assessment on voltages. The red line is the maximum voltage limit (1.1 p.u.).

starting from 80% PV penetration. For example, 34% of the simulations at 100% residential PV penetration results in voltages above the upper limit. The cause of voltage excursions is that the sizes of PV and batteries are determined from customers' perspective only based on the minimum capital cost of the system which results in increasing PV sizes and with the minimum required sizes of batteries. Further, most of the resulting sizes of residential batteries are likely to be fully charged before critical periods around noon. Therefore, alternative strategy is necessary to mitigate impacts on distribution networks.

D. PV-Self Consumption with Batteries: DNO-Led Strategy

In this case, the uptake of batteries is led by distribution network operators to reduce the PV impacts on distribution networks whilst still enabling customers to achieve the desired PV-self consumption levels.

To demonstrate the implications of the *DNO-led* strategy on the sizes of PV and batteries, the unit cost of battery per kWh in equation (8) is set to be smaller than the unit cost of the of the PV rating per kW. Further, 40% and 50% PV self-consumption levels are adopted for illustration purposes. The sizes at 100% PV penetration are given in

TABLE V. It can be noticed that the *DNO-led* strategy results in significant reduction in the required PV sizes by 14% and 36% to achieve 40% and 50% PV self-consumption levels, respectively compared to the sizes in the user-led strategy. However, the DNO-led strategy supports the adoption of larger sizes of batteries for both PV self-consumption levels. For instance, the required sizes of batteries at 40% PV self-consumption level are increased from 1.2 MWh in the user-led strategy to 2.4 MWh in the DNO-led strategy. This in turn may reduce the volume of excess PV generation exported to the grid, thus increasing the PV penetration without the violation of network constraints.

1) DNO-Led Strategy without Excess-Power Thresholds

To understand the maximum PV penetration to which the *DNO-led* strategy can mitigate the PV impacts without the need to impose additional constraints on charging, the management of batteries will be carried out considering an excess-power threshold of zero ($\varepsilon^{threshold} = 0\%$). Like the management approach adopted at the *user-led* strategy, batteries are allowed to freely charge as much as possible of the available excess PV generation. Fig. 15 shows the voltage results for different PV penetration and considering 40% PV self-consumption level. It can be noticed that the first PV penetration resulting in voltages above the upper limit is at a PV penetration of 100% compared to 80% at the *user-led* strategy. However, the impacts from residential PV will still be seen on the network at 100%

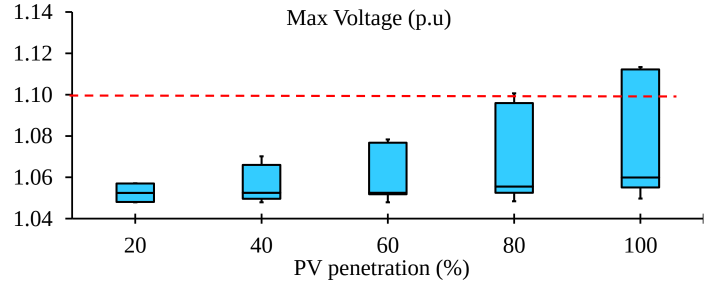

Fig. 15. *DNO-led* battery strategy with 40% desired PV self-consumption level: impacts assessment on voltages. The red line is the maximum voltage limit (1.1 p.u.).

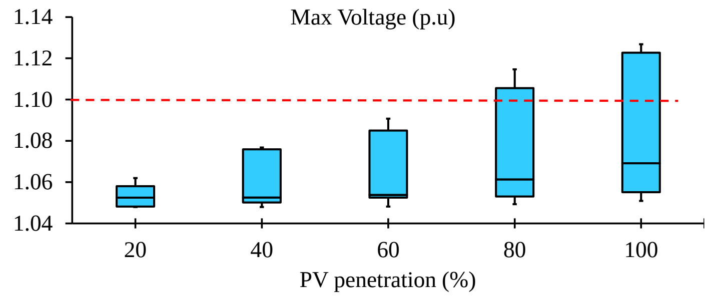

Fig. 16. *DNO-led* battery strategy with 50% desired PV self-consumption level: impacts assessment on voltages. The red line is the maximum voltage limit (1.1 p.u.).

residential PV penetration. Further, larger impacts are found at 50% PV self-consumption level as can be seen in Fig. 16.

2) DNO-Led Strategy with Excess-Power Thresholds

This section aims to demonstrate the PV impacts of the *DNO-led* strategy with the adoption of constraints on charging using *excess-power threshold*. To define the most adequate power threshold, both the maximum voltages and the average PV self-consumption levels across residential customers are assessed for different values of *excess-power thresholds* with steps of 10% (10%, 20%, …, 100%). The impacts on voltages results and PV self-consumption levels are given in

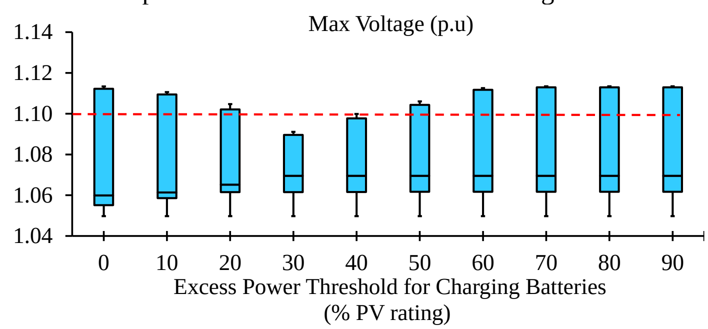

Fig. 17 and Fig. 18, respectively considering 40% PV self-consumption and at 100%

PV penetration. It can be noticed that the adoption of *excess-power threshold* either smaller than 20% or larger than 40% will result in voltages outside the limits. However, the selection of power threshold larger than 30% will reduce significantly the PV self-consumption level. For instance, the reduction may reach 4% with power threshold above 50%. Therefore, the most adequate value of power threshold lies between 20% and 30%.

To tune the best value of *excess-power threshold*, the impacts on voltages and PV self-consumption levels are both assessed for different values of excess-power thresholds between 20% and 30% considering a step of 1% (21%, 22%, 23%,…, 30%). It is found that the adoption of an *excess-power threshold* of 25% can effectively mitigate the PV impacts on distribution networks whilst achieving a PV self-consumption level of 39% (very close to the desired one of 40%).

To define the best value of power threshold at 50% PV self-consumption, the same process is adopted. Fig. 19 and

Fig. 20 present the impacts on voltages and PV self-consumption levels, respectively. Here, it is found that the most adequate *excess-power threshold* to mitigate the PV impacts with the minimal effects on customers is 20%. However, the maximum possible PV self-consumption level is only 47 % which is smaller than the desired one by 3%. This shows the importance to adopt

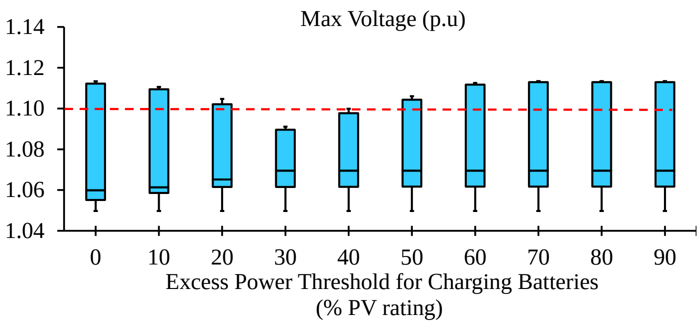

Fig. 17. *DNO-led* strategy with 40% desired PV self-consumption at 100% PV penetration: impact assessment on voltage for different excess-power thresholds. The red line is the maximum voltage limit (1.1 p.u.).

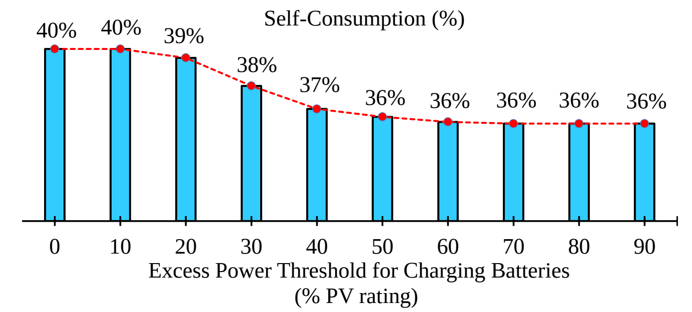

Fig. 18. *DNO-led* strategy with 40% desired PV self-consumption at 100% PV penetration: average PV self-conumption for different excess-power thresholds

adequate incentives schemes to compensate the reduction in PV self-consumption in exchange of network management.

E. Remarks

For the benefits of the readers, the key remarks resulting from the application of the proposed framework to the real MV-LV distribution networks are summarized as follows:

- The net-metering policy encourages residential customers to increase PV exports to the grid to reduce their electricity bills to zero. However, this will lead to voltage rise issues on distribution networks. The Monte-Carlo simulations show that the uptake of residential PV penetration above 40% will increase voltages above the statutory limit (1.1 p.u.). This will also limit the PV self-consumption level to 17%. Thus, alternative PV policy is important to enable the wide-scale PV adoption and improve PV self-consumption.
- The adopted integrated MV-LV network models provide a more accurate assessment of PV impacts on distribution networks compared to the LV-only models. The results demonstrate that the LV busbar voltages can reach 1.065 p.u. during a high PV production day. This highlights the benefits of the integrated models to capture voltage interactions between MV and LV compared to the adoption of an arbitrary fixed LV busbar voltages (e.g., 1 p.u.) in the LV-only models. Also, this shows that the LV-only models may underestimate the PV impacts on distribution networks.
- In the PV self-consumption policy, the export energy is remunerated at a much smaller rate than the import energy price. Hence, this policy encourages customers to improve the share of PV in the local energy consumption needs and reduce PV exports to the grid. The simulations show that the PV self-consumption policy (PV-only without batteries) enables better utilization of the hosting capacity of

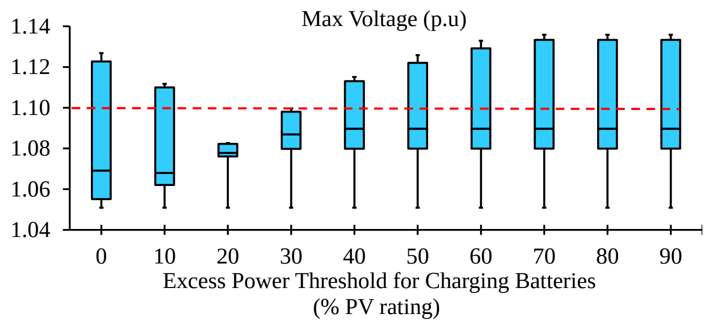

Fig. 19. *DNO-led* strategy with 50% desired PV self-consumption at 100% PV penetration: impact assessment on voltage for different excess-power thresholds. The red line is the maximum voltage limit (1.1 p.u.).

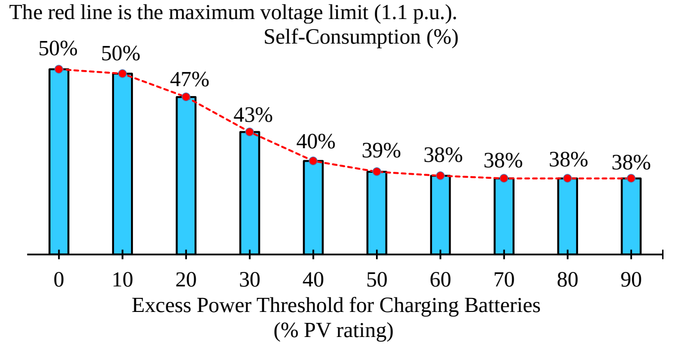

Fig. 20. *DNO-led* strategy with 50% desired PV self-consumption at 100% PV penetration: average PV self-conumption for different excess-power thresholds.

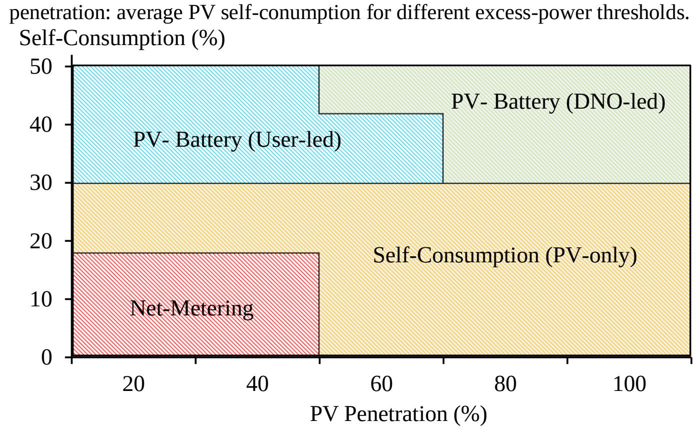

Fig. 21 Performance matrix for PV policies: the maximum PV penetration (%) and PV self-consumption level (%) that could be achieved per each PV policy without the violations of network constraints.

distribution networks to support 100% residential penetration compared to 40% in the net-metering. Therefore, more customers are enabled to reduce their electricity bills in the PV self-consumption policy. However, the PV self-consumption level is limited to 30%.

- Residential PV coupled with batteries in the PV self-consumption policy reduces significantly the import energy. However, deciding the optimal sizes and managing batteries from the perspective of customers (user-led strategy) will not mitigate the PV impacts. The results demonstrate that the PV impacts will still be seen with PV penetration above 60%. Thus, new rules or alternative ownership models are needed to ensure harnessing the capabilities of batteries to solve distribution network issues.
- The results demonstrate the important role of DNOs to manage the uptake of batteries for the benefits of both customers and distribution networks. DNOs can support customers to adopt larger sizes of batteries to achieve the desired PV self-consumption in return of controlling the batteries to solve network issues. This strategy facilitates the uptake of 100% PV penetration and improves PV self-consumption to 50%. However, adequate regulatory incentive schemes have to be in place to support DNOs and enable achieving the potential benefits.
- In the DNO-led strategy, the charging operations of batteries are managed to limit the excess PV generation below a predefined excess-power threshold to solve network issues with minimal impacts on customers. The results show that the most adequate value of excess-power threshold from the perspective of both distribution networks and customers at 100% PV penetration is 20% of the PV rating.
- For completeness, Fig. 21 compares the performance of different PV policies. Both the maximum PV penetration and the maximum PV self-consumption level that could be obtained per each PV policy without the violations of network constraints are presented.

VII. Discussions

This Section presents the limitations for the work carried out. These limitations can be considered as the future research to be undertaken.

To find the optimal sizes of PV and batteries based on the adopted PV policy, a MILP optimization model is formulated and it is solved using the CPLEX solver. However, other optimization approaches such as genetic algorithms and particle swarm optimization can be adopted to solve the optimization problem. A comparison against other optimization approaches has not been provided in this work. The provision of this comparison in terms of accuracy, complexity and computational burden can be considered as one of the future research to be undertaken. This is not the focus of this work.

The impacts of net-metering and PV self-consumption policies on distribution networks are quantified in terms of voltage issues and congestions. Future research can be also carried out to quantify the economic impacts related to the required network reinforcements to mitigate the technical impacts on distribution networks. However, this requires the development of a methodology to determine the cost of reinforcements in terms of MV and LV lines and MV/LV distribution transformers.

Although the economic impacts of each PV policy on customers are quantified in terms of PV self-consumption, the exact revenues and costs are not provided. Future works could be also carried out to assess the profitability for customers. This requires set of financial parameters such as the cost of PV and batteries, retail electricity prices and maintenance cost. To draw general recommendations, thorough sensitivity analysis is also required to understand the effects of varying these parameters either individually or simultaneously. This is not the focus of this paper. It is worth to highlight that the first stage of the planning framework is general and it can be adapted to explicitly consider all these financial parameters.

The results also demonstrate the important role of DNOs to manage the uptake of batteries for the mutual benefits of both distribution networks and customers. However, this requires the development of new regulation rules to enable the implementation of the proposed DNO-led strategy in practice. In particular, adequate incentive schemes have to be in place to support DNOs and enable achieving the potential benefits of the DNO-led strategy. The incentive schemes can be set on the basis of the volume of PV and batteries connected to the network, the reduction in the connection time and the avoided cost of network reinforcements. These incentives and the contributions of DNOs in batteries can be recovered from network users in the form of daily network charges, e.g., $/day. It is also worth to highlight that the adoption of DNO-led strategy might be more effective in countries with regulations that authorize DNOs to both manage distribution networks and retail electricity to customers (e.g., Jordan). Thus, this direct access between DNOs and customers can facilitate the development of future commercial agreements related to batteries.

Future work can be also undertaken to assess the potential to exploit the capabilities of batteries to provide additional services particularly flexibility and grid services to the system operator, e.g., provision of reserve services. Although the provision of these services will improve the financial viability of batteries, the impacts on distribution networks should be also adequately understood.

VIII. Conclusions

This work presents a two-stage planning framework that aims to assess the implications of departing from the existing net-metering Photovoltaic (PV) policy to future PV self-consumption policy to enable the wide-scale adoption of residential PV and improve PV self-consumption whilst respecting the constraints of distribution networks. The proposed two-stage planning framework assesses the impacts of PV and batteries on distribution networks per PV policy, per PV penetration (number of customers with PV) and per desired PV self-consumption level.

The framework is demonstrated on real Jordanian medium-low voltage distribution network. The first stage (Mixed Integer Linear Programming optimization problem) was effective in producing the minimum sizes of PV and batteries to achieve a desired PV self-consumption.

The results also show the effectiveness of the second stage to assess the impacts on network voltages and congestions using Monte Carlo simulations to cope with uncertainties in demand and generation. Also, the integrated medium-low voltage distribution network modelling enables capturing the power flows and voltages interactions between medium voltage and low voltage to adequately assess the impacts.

The results show that the definition of electricity bills based on the import energy in the PV self-consumption policies (no reward is given to the export energy) restricts the sizes of PV installations compared to the net-metering. This in turn results in better utilization of the hosting capacity of the analyzed network to serve larger number of PV installations. The simulations show that the PV self-consumption policy (without batteries) enables 100% residential PV penetration compared to only 40% in the net-metering. Therefore, the PV self-consumption supports more customers to reduce their electricity bills than in the net-metering.

Further, the analysis demonstrates the role of batteries to improve PV self-consumption. However, it is found that deciding PV and batteries sizes from customers' perspectives (*user-led Strategy*) will not mitigate the PV impacts. This is due to the adoption of small sizes of batteries to minimize the overall installation cost. Further, the management of batteries for the benefits of customers (to harvest as much as possible excess PV generation) will fully charge these devices before the critical periods around noon (maximum PV generation and minimum demand).

The results also show the important role of Distribution Network Operators (DNOs) to manage the uptake of batteries to increase PV penetration and improve PV self-consumption. Distribution network operators can support customers to adopt larger sizes of batteries to achieve the desired PV self-consumption in return of controlling the batteries to solve network issues. Also, adequate regulatory incentive schemes have to be in place to support distribution network operators and enable achieving the potential benefits. This DNOs-led strategy reduces PV sizes and thus PV exports. To solve network issues at high PV penetration and high PV self-consumption, the charging operation of batteries is also modified. This is done by managing the excess PV generation below a predefined excess-power threshold. The results show that the adoption of small excess-power threshold to trigger charging is found effective to achieve the desired PV self-consumption. However, this results in quickly fully charging the batteries and the violation of network constraints. Although the adoption of large power threshold is adequate to delay the time periods when the batteries are fully charged, the PV impacts on distribution network are still seen and the desired PV self-consumption are also affected. After assessing the impacts of different values of excess-power threshold on both customers' PV self-consumption and distribution networks, an adequate excess-power threshold is found to manage network constraints with minimal impacts on customers.

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