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Effect of tariffs on the performance and economic benefits of PV-coupled battery systems

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HIGHLIGHTS

- Pb-acid and Li-ion batteries are compared under three different retail tariffs.
- The battery ageing, i.e. capacity and discharge capability reduction is simulated.
- A dynamic tariff (1-h resolution) increases the battery discharge value up to 28%.
- A Li-ion cost of 375 CHF/kW h is required for Geneva for PV energy time-shift.
- This requirement becomes 500 CHF/kW h if demand peak-shaving is also performed.

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ABSTRACT

The use of batteries in combination with PV systems in single homes is expected to become a widely applied energy storage solution. Since PV system cost is decreasing and the electricity market is constantly evolving there is marked interest in understanding the performance and economic benefits of adding battery systems to PV generation under different retail tariffs. The performance of lead-acid (PbA) and lithium-ion (Li-ion) battery systems in combination with PV generation for a single home in Switzerland is studied using a time-dependant analysis. Firstly, the economic benefits of the two battery types are analysed for three different types of tariffs, i.e. a dynamic tariff based on the wholesale market (one price per hour for every day of the year), a flat rate and time-of-use tariff with two periods. Secondly, the reduction of battery capacity and annual discharge throughout the battery lifetime are simulated for PbA and Li-ion batteries. It was found that despite the levelised value of battery systems reaches up to 28% higher values with the dynamic tariff compared to the flat rate tariff, the levelised cost increases by 94% for the dynamic tariff, resulting in lower profitability. The main reason for this is the reduction of equivalent full cycles performed with by battery systems with the dynamic tariff. Economic benefits also depend on the regulatory context and Li-ion battery systems were able to achieve internal rate of return (IRR) up to 0.8% and 4.3% in the region of Jura (Switzerland) and Germany due to higher retail electricity prices (0.25 CHF/kW h and 0.35 CHF/kW h respectively) compared to Geneva (0.22 CHF/kW h) where the maximum IRR was equal to −0.2%.

1. Introduction

Many countries are reviewing their energy policies to position themselves on the global energy arena and address the "trilemma" of security of supply, affordability and decarbonisation [1,2]. Within this context, renewable energy (RE) technologies are in the spotlight since they have the potential for converting different world economies into sustainable in contrast to fossil fuels. After the accident at the Fukushima Diichi nuclear power plant in March 2011, the Swiss parliament decided to phase out all nuclear plants as part of a more comprehensive energy strategy which focuses on substantially reducing final energy and stabilising demand for electricity [3]. The Swiss Energy Strategy 2050 moreover foresees a reduction of greenhouse gas (GHG) emissions by 20% in 2020 and by a factor of 5 by 2050 and in comparison to 1990.

Several developments call for the use of energy storage (ES) across different sectors and scales in Switzerland within the new energy policy. Nuclear power plants will be mainly replaced by RE plants including hydropower, PV and wind generators, with

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Nomenclature

C	battery capacity, kW h
CF	cash flow, £
D_{ES}	proportion of the total demand met by a battery system
E_{char}	seasonal battery charge, kW h
E_d	seasonal demand of a single dwelling, kW h
E_{dis}	seasonal discharge, kW h
E_{PV}	seasonal PV generation, kW h
E_{PVES}	seasonal PV energy supplied to a battery system, kW h
h	hour
IRR	internal rate of return
k	generic year
$LCOES$	levelised cost of energy storage, CHF/kW h
$LVOES$	levelised value of energy storage, CHF/kW h
n	number of years the battery lasts
P	electricity price, CHF/kW h
PV_{ES}	proportion of the PV generation supplied to a battery system
r	discount rate (%)
Rev	battery revenue, (CHF)
$TLCC$	total levelised cost, CHF

Z	linear durability coefficient of a battery technology, %/EFC
η	round trip efficiency

Acronym

DT	double tariff
DynT	dynamic tariff
EFC	equivalent full cycles
ES	energy storage
Li-ion	lithium ion
PbA	lead acid
PV	Photovoltaics
PVts	PV energy time-shift
SOC	state of charge
ST	single tariff

Subscripts

nom	nominal
rt	retail
wh	wholesale

only the first offering matching capability. Specifically, 24 TW h of wind and PV generation are expected by 2035 [3] and the number of end users who own a RE plant will increase following the developments in other countries such as Germany, UK and Spain. Secondly, the last reform of the Swiss electricity market in 2009 included its partial liberalisation [4]. Customers with an annual consumption larger than 100 MWh can access the electricity market independently or freely choose their best electricity supplier. Market liberalisation is also envisaged for small consumers during this decade and new business models based on RE plants (heat and electricity), smart meters and different tariffs, thereby involving end users, utilities and/or ESCOs (energy service companies) are being explored [5].

The range of ES technologies available in the market and applications they can perform is wide and they have been compared in many review papers and reports [6–9]. Typically, ES technologies (and applications as a result) are classified using different criteria including electricity and heat storage, the duration of discharge and the scale (distributed versus bulked storage). Distributed ES is receiving marked attention due to the increasing penetration of RE technologies next to the locations of energy consumption [10]. There has been particularly strong interest in battery storage for managing PV generation in single homes since battery systems offer good capability to perform daily cycles while discharging for several hours with negligible self-discharge [11]. Many articles have been published in the last years on the technical and economic performance of battery systems. A high level of interest is sustained by the accelerated penetration of PV systems (in the last ten years, the cumulative installed capacity has grown at an average rate of approximately 50% per year [12]); increasing retail energy prices; and the decreasing prices and continually improved performance batteries.

Previous research which addressed the economic benefits of batteries systems for single homes mainly considered battery systems which were only charged by on-site PV plants and assumed constant round trip efficiency and durability [5,13–16]. A specific battery chemistry, typically either lead-acid (PbA) or lithium-ion (Li-ion), performing PV management by increasing the amount of local PV generation used at home was typically included in the study. The self-consumption as a function of the battery capacity was traditionally simulated, the economic benefits being calculated for the regulatory context of the respective country including Germany [5], UK [14], Portugal [15], Spain [16] and Belgium [13]. Local sensitivity analysis is typically the preferred technique used to tackle the uncertainty related with the modelling results depending on the input parameters, e.g., storage medium cost and electricity prices. The main novelties introduced by recent studies are: optimisation of both PV array rating and battery capacity (two degrees of freedom) without feed-in tariffs and calculation of economic revenue due to the difference between constant retail prices and constant wholesale prices [5]; calculation of the economic revenue depending on the investment year between 2013–2022 [5] and 2012–2021 [13] and for different remuneration schemes (subsidies, market prices and no fees at all); the inclusion of an environmental analysis [14]; the consideration of local and grid benefits for the different applications including self-consumption, reduction of the peak grid import, reduction of the peak electricity injected into the grid as well as integration of wind power from a national point of view [15]; and the combination of ES and active demand-side management managed by neural network controllers [16].

Focusing on communities ranging from a single home to a 100-home community, the performance and the economic benefits of PbA and Li-ion battery systems have also been analysed [17]. It was concluded that the levelised cost of meeting the demand load using PV energy decreased up to 37% for a 10-home community compared with the single home due to different benefits introduced by the community approach including less severe discharge rates, higher round trip efficiency and economy of scale. A different approach was also taken into account by Zucker and Hinchliffe [18] and domestic battery systems performing PV energy time-shift and arbitrage on the wholesale market were optimised from the perspective of an aggregator trading power on wholesale markets. The authors identified the optimum discharge time (5 h), power rating (40% of nominal PV capacity) and required capital cost (100–150 €/kW h). Tant et al. presented a multiobjective optimisation method for PbA and Li-ion batteries connected to three single-phase inverters in a low voltage (230/400 V) semiurban distribution grid. Three different applications were optimised, namely voltage regulation, peak power reduction and annual battery total cost including electricity prices [19]. Battery storage was not required for low investment solutions (lower than €1500 p.a.) based on the capability of three single-phase inverters to distribute power between phases; and the techno-economic results were very similar for PbA and Li-ion batteries under the assumption that the Li-ion cell cost is four times higher. Finally, three types of time-of-use tariffs including off-peak, day and peak periods were investigated for a 20.6 kW h PV-coupled PbA battery system in the UK and Ireland (under the current subsided export tariff equal to 3.2 p/kW h). It was concluded that extra benefits were small (20£p.a.) compared with a flat rate tariff because those time-of-use tariffs offered "day" period prices which were very similar to the standard flat rate price [20].

Considering the literature review above, there is still a lack of understanding about the economic benefits brought by PV-coupled battery systems accounting for: type of technology (PbA and Li-ion battery systems since both technology options are available in the market at the moment); battery ageing; round trip efficiency and equivalent full cycles as a function of the battery capacity; variable wholesale prices; and dynamic retail tariffs. Additionally, economic benefits have been previously calculated based on feed-in tariffs schemes which vary significantly depending on the country and they have been modified repeatedly in the last years in different European countries [21]. In order to make the calculation independent of any specific legislation and considering that feed-in tariff incentives have been reduced in countries such as Germany, Spain and Switzerland, it was assumed that PV generators sell electricity to the wholesale market, as other generators do. This new methodology will allow us to answer the following research questions: (i) what is the optimum battery system including technology (PbA and Li-ion), battery capacity and how this optimum is affected by the type of retail tariff?; and (ii) how are economic benefits affected by the regulatory context and by different value propositions? The rest of this paper has the following structure. Section 2 introduces the methodology followed in this paper to study the techno-economic behaviour of the battery systems including the battery model, input data for the baseline scenario and time-dependant optimisation method. Results from the baseline scenario are presented in Section 3 and they are compared to alternative scenarios in Section 3.3. Besides, a sensitivity analysis is performed in order to tackle the uncertainty associated with the input data in Section 4. Finally, Section 5 discusses the implications of the results for end users purchasing a PV-coupled battery system and Section 6 concludes this paper.

2. Assessment methodology

This paper focuses on PV-coupled battery systems by analysing the techno-economic implications of adding a battery system to a pre-existing PV system (the PV system is not evaluated economically) in Geneva (Switzerland). Before the installation of the battery storage system, PV generated electricity is assumed to only be used to meet the local demand of the dwelling (replacing grid import with a retail electricity price) or it is exported to the grid when it exceeds the local demand (at the wholesale electricity price). It was assumed that the battery system on-site is only charged with electricity generated by the PV system; the battery system hence serves to perform PV energy time-shift to meet the local demand later. In contrast, demand load shifting, i.e. charging the battery with grid electricity is not included in the analysis (this in line will all references discussed in the previous section which focused on batter storage in single dwellings). Fig. 1 shows a schematic representation of a battery system for a single home connected to a PV array and including the required electronic equipment as modelled in this work [5,22]. The revenue (or, actually, avoided cost) of a PV-coupled battery system is calculated using Eq. (1) and it is driven by the difference between the price of the electricity imported from the grid by the end user (owner of the battery system) depending on tariff (see Fig. 5), P_{rt} (CHF/kW h), and the price of the electricity exported (wholesale electricity price), P_{wh} (CHF/kW h). In 2014, the latter was less than one third the retail price, making battery discharge to the grid unprofitable [23,24]. In Eq. (1), E_{char} (kW h) and E_{dis} (kW h) is the battery charge and discharge respectively during any hour (the total number of hours in a year being h equal to 8760 h).

$$Rev_{PVts} = \sum_{h=1}^{8760} E_{dis} \times P_{rt} - \sum_{h=1}^{8760} E_{char} \times P_{wh} \tag{1}$$

A primary energy balance was prepared for the battery system as a physical system and the surroundings including PV generation and electrical demand. The technical performance of the system was analysed by means of the following indicators: the round trip efficiency of the battery system, η, and the equivalent full cycles (EFC) defined as the number of cycles performed by the battery system using the whole depth-of-discharge throughout the battery lifetime. The selected parameters for analysing the impact of a battery system in a dwelling are the share PV_{ES}, of stored PV electricity, E_{PVES} (kW h/year), to total electricity generated by the PV system, E_{PV} (kW h/year), instead of being used instantaneously within the dwelling or directly exported to the grid. The share of battery self-consumption, SC_{ES}, was also analysed as defined by Eq. (3) in which E_d (kW h/year) refer to the annual demand of the single dwelling.

$$PV_{ES} = \frac{E_{PVES}}{E_{PV}} \tag{2}$$

$$SC_{ES} = \frac{E_{dis}}{E_d} \tag{3}$$

The economic indicators used to asses the battery performance are the levelised cost of ES, *LCOES* (CHF/kW h), the levelised value of ES, *LVOES* (CHF/kW h), and the internal rate of return, *IRR* (%). The two first indicators quantify the cost and value associated with the discharge of a battery system added to a PV system while the *IRR* is a measurement of the profitability of the battery investment. The investment cost of the PV panel is not included in the analysis because it is assumed to be pre-existing while the effects of additionally installing a battery system were studied. The three economic indicators are defined by Eqs. (4)–(6) respectively. *TLCC* (CHF) refers to the total levelised cost including the storage medium, inverter, balance-of-plant and maintenance cost throughout the life of the project considering the value of money over time. CF_k represents the future cash flows including the battery expenses and revenues throughout the battery lifetime (n years). The *IRR* is the discount factor for which the sum of all net present values of the cash flows, CF_k, related to the battery investment is equal to zero (see Eq. (6)). By using levelised values, results account for the durability of the battery system, available PV charge and selected battery capacity for the given application. Fig. 2 displays the indicators utilised in this work for assessing battery systems performing PV energy time-shift in single dwellings.

$$LCOES = \frac{TLCC}{\sum_{k=0}^{n} \frac{E_{dis}}{(1+r)^k}} \tag{4}$$

$$LVOES = \frac{\sum_{k=1}^{n} \frac{CF}{(1+r)^k}}{\sum_{k=0}^{n} \frac{E_{dis}}{(1+r)^k}} \tag{5}$$

$$\sum_{k=0}^{n} \frac{CF_k}{(1+IRR)^k} = 0 \tag{6}$$

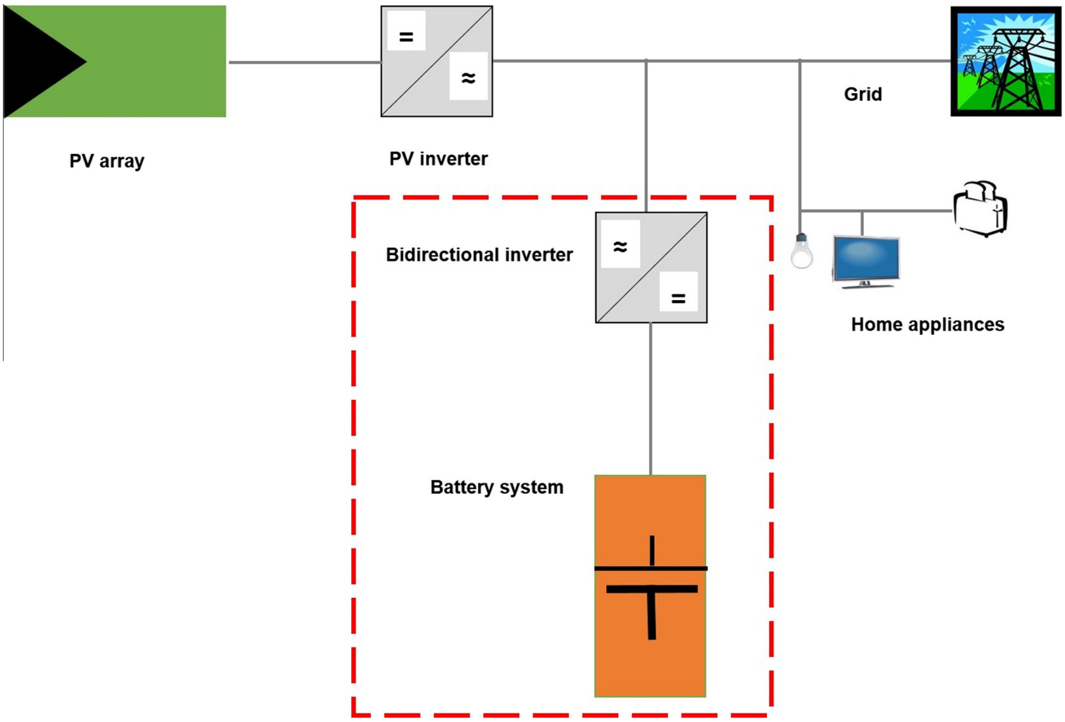

Fig. 1. Schematic representation of a battery storage system for a single dwelling including the main components as studied in this work. The battery system is framed to emphasise that the PV array system in not economically analysed. Also, it is assumed that the battery system is only charged from the PV array.

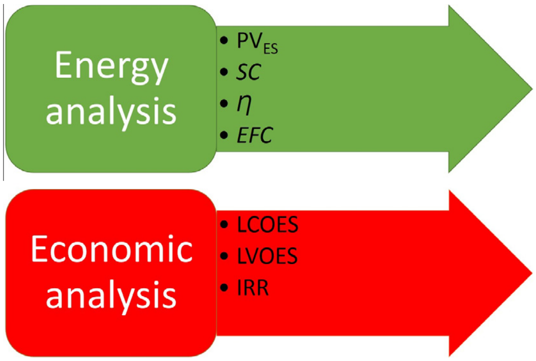

Fig. 2. Indicators utilised in this work to compare PbA and Li-ion batteries performing in a single dwelling.

In order to apply the assessment methodology, several input data are necessary to characterise the PV generation, demand load, battery technology and the economic and regulatory context. A temporal resolution of 1 min was utilised for the PV generation and demand data. Therefore, the battery model introduced below is simulated with the same temporal resolution allowing to capture the impact of the PV generation and demand load mismatch on the battery performance. These various input data are presented below in addition to the battery models and algorithm utilised to optimise PV energy time-shift for PbA and Li-ion battery systems.

2.1. Demand data

A single home in the UK with an annual electricity consumption equal to 3.4 MW h was utilised [25,26] since no similar data were available for Switzerland. The demand data set utilised in this work was monitored in a residential community for a total of 129 dwellings and was utilised in other previous studies [27,26,28]. The use of the UK dataset is justified and representative of the current stock of houses because the aggregated electricity demand (3.4 MW h/year) is equivalent to the demand of the "average" household in Switzerland in 2012 [29].

2.2. PV generation

Global horizontal irradiance (W/m^2) over one year was measured using a weather station which incorporates a pyrometer at the University of Geneva in addition to other environmental variables including outdoor temperature [30]. For the model, it was assumed that the PV array is tilted at angle of 30° which is the case for most PV arrays already installed in Geneva. As a consequence, the global horizontal irradiance was transformed into tilted irradiance using a sky model presented by Duffie and Beckman [31]. The output of any PV panel is mainly affected by the irradiance and the temperature, in this order, and a single diode model was utilised to obtain the electricity generated by the PV panel [32]. The PV panel selected (the HIT-N235SE10 manufactured by Sanyo) uses silicon monocrystalline technology with a maximum module efficiency of 18.6% [33]. The rating of the PV array was set to 3 kW$_p$ in agreement with the average PV rating for single homes in the Germany [13] and UK [34] (this value is not available for Switzerland at the moment). Fig. 3 represents the PV generation during a winter day, summer day and throughout the year. This PV system was able to meet 29.3% of the annual demand of the single home while the 70.7% of the annual PV generation was exported to the grid.

2.3. Battery model

The lack of ES models which consider the performance and durability to calculate the economic benefits is one of the key gaps preventing a full understanding of ES benefits [17]. This study overcomes this drawback by using comprehensive and identically structured models for both PbA and Li-ion batteries which include

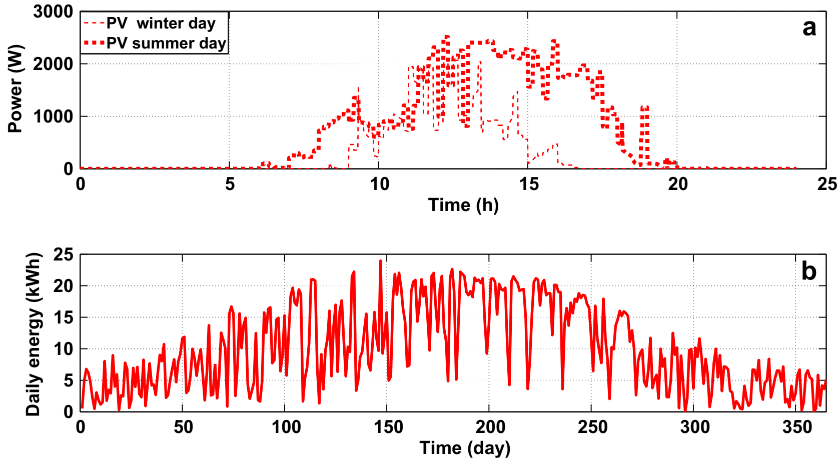

Fig. 3. PV generation from a 3 kW$_p$ PV array in Geneva during (a) a summer day (22/06/2013) and winter day (17/12/2013); and (b) daily PV generation during the year 2013.

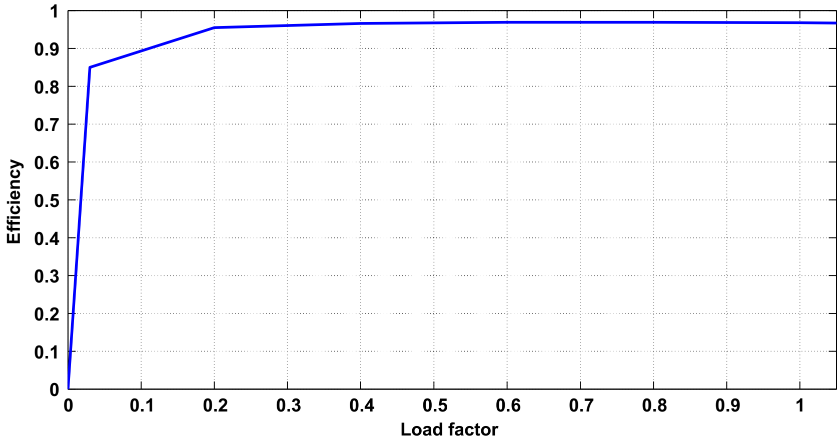

Fig. 4. Inverter efficiency as a function of the load factor [35].

Table 1
Comparison of technical and economical characteristics of PbA and Li-ion battery systems.

Parameter (Unit)	PbA	Li-ion
Maximum charge current (A)	$0.2 \cdot C_{nom}$	$3 \cdot C_{nom}$
Maximum discharge current (A)	$0.4 \cdot C_{nom}$	$3 \cdot C_{nom}$
ΔSOC	0.5	0.8
Maximum SOC	0.9	0.9
Minimum SOC	0.4	0.1
Inverter rating (kW)	3	
Storage medium cost (CHF/kW h)[a]	200	500
3 kW Inverter cost (CHF)[b]	1615	1615
Balance-of-plant cost (CHF/kW)[c]	100	
Maintenance cost (CHF/kW)[c]	10	
Maximum cycle life (EFC)[d]	1500	4000
Z (%/EFC)	0.02	0.0075
Maximum calendar life (years)[d]	18	22
Calendar losses (%/month)[e]	0.12	0.07

[a] From available literature [9,43,44] and confirmed with experts.
[b] Current cost based on data from SMA Solar Technology AG [35].
[c] Based on published data from the Department of Energy (DOE) [45].
[d] From available literature [44,8,46] and confirmed with manufacturers including Solom and Hitachi.
[e] Monthly battery capacity percentage reduction.

the performance, durability and economic behaviour. Since the full description of the ES model approach including specific submodels can be found in the references above only key details and characteristics are summarised in this section.

The performance submodels represent the voltage variation of battery systems connected to RE generators and variable demand loads for PbA [36] and Li-ion [37–39] technologies. This is accomplished by considering the impedance (resistance [36] and a resistor–capacitor circuit [38] for PbA and Li-ion batteries respectively) in series with the open-source voltage, with all parameters varying as a function of the state-of-charge (SOC). The performance submodel also includes the bidirectional inverter necessary for the electricity to be managed by the battery system. The efficiency curve of current state-of-art inverters manufactured by the company SMA Solar Technology AG was used for this purpose [35] and is shown in Fig. 4. The input data necessary for the performance submodels include the maximum charge/discharging rating, depth-of-discharge, maximum SOC and minimum SOC (see Table 1). Companies like Hitachi, Saft and Solom in addition to an expert were consulted for these data. The durability submodel considers both cycle and calendar losses in order to determine the battery capacity reduction [40]. Cycle losses, ΔC (A·h), were calculated using Eq. (7) and they were assumed to be linear to the decrease in the state of charge, (ΔSOC), and the nominal battery capacity, C_{nom} (A·h), within the discharge limits shown in Table 1 when considering a coefficient characteristic of any battery technology (Z) [41,42]. The coefficient Z was determined assuming that the battery management system not only prevents the SOC to exceed the limits shown in Table 1 but also controls the battery temperature according to safe and efficient standards. Regarding the calendar losses, the Arrhenius formula was used to model the temperature effect when the battery system is not operating [38]. According to this modelling approach, a larger battery capacity implies a longer durability for the same performance conditions. The performance and durability submodels were utilised to quantify the performance indicators shown in Fig. 2 considering the reduction in battery capacity and lifetime of battery systems.

$$\Delta C = Z \times C_{nom} \times \Delta SOC \quad (7)$$

The input data necessary for the economic assessment included the capital expenditure (CAPEX), operating expenditure (OPEX), the discount rate applied to the investment, the electricity wholesale and retail prices. Table 1 compares the cost data for PbA and Li-ion batteries with CAPEX cost being broken down into storage medium, inverter and balance-of-plant costs. A discount rate equal to 4% was selected, which is in the range of those utilised in previous studies of single-home battery systems [5,13,15].

2.4. Energy prices

Retail electricity prices decreased in Geneva by 2.4% p.a. from 2010 to 2014 but they markedly increased by 15.7% at the beginning of 2015 [23]. Other regions in Switzerland have experienced similar trends and electricity prices are expected to increase in the coming years due to the implementation of RE technologies and energy efficiency measures related to the phase-out of nuclear power plants [47]. In the case of Germany which also legislated the phase out of its nuclear plants, retail electricity prices increased by an average rate of 5.7% p.a. in the last four years [48]. Other European countries have experienced substantial increases in recent years including Spain (63% from 2008 to 2013, i.e. 10% p.a.) and UK (46% from 2007 to 2013, i.e. 6.5% p.a.). According to these data, a retail price increase equal to 5% p.a. in Switzerland was assumed as a first attempt to model the expected rise of retail tariffs. this translates into an increase of the electricity price in Geneva from currently 0.22 CHF/kW h (2015) to 0.29 CHF/kW h and 0.47 CHF/kW h by 2020 and 2030 respectively.

The wholesale prices in Switzerland are derived in the EPEX SPOT market which is the exchange for the power spot markets covering France, Germany, Austria and Switzerland [24]. Within this platform, generators and retailers specify their position hourly and every 15-min for the day-ahead market and the intraday market respectively. Although intraday markets are becoming more relevant due to the increasing penetration of RE energy generators which calls for shorter time periods to accurately forecast their outputs in advance, they only accounted for 5% of the total electricity traded in France, Germany, Austria and Switzerland in 2012 [24]. Contrary to the development of retail prices discussed above, wholesale prices have fallen for the last four years by 37.2% and 37.9% in Switzerland and Germany respectively (regarding 2011). Since they are expected to remain stable in Europe until 2020 according to the latest projections from the European Energy Exchange [49], wholesale prices were assumed to remain constant and prices from the day-ahead market for Switzerland in 2013 were utilised (which is the most recent year for which the complete dataset was accessible, the average wholesale electricity price being equal to 55.9 CHF/MW h).

Three different types of retail prices were considered. The retail price for the baseline scenario was assumed to be a tariff with a constant electricity price for every day of the year (yet increasing every year, see above). For this purpose, the electricity price in Geneva in 2015 according to the tariff "Profil simple" (referred to as "simple tariff" abbreviated as ST) from the company Services Industriels de Genéve (SIG) was utilised [23]. Alternatively, a 2-period Time-of-use tariff (with a valley and peak period) offered by the same utility company is considered as a simple approach for accounting for a more dynamic tariff structure. This tariff, referred to in this study as "double tariff" (abbreviated as DT), has also been implemented in other countries including the UK and Spain in order to promote the smoothing of the daily peak demand by using more cost-effective based load generation [26]. A third tariff based on the wholesale market prices in Switzerland described above (and referred to as "dynamic tariff" in this study or DynT) is included in order to understand the economic benefits of battery storage in the case of dynamic retail prices. In addition to the price component reflecting the wholesale market, the dynamic tariff includes the other three components which constitute the final retail price, i.e. electrical network usage, community services and RE incentives. The latest data available from the Swiss Federal office of Energy was used for this purpose, which is equal to 0.09 CHF/kW h, 0.02 CHF/kW h and 0.01 CHF/kW h respectively [50]. The resulting total wholesale price ranges from 0.12 to 0.46 CHF/kW h. Fig. 5 shows the three different retail prices compared in this study. The total utility revenue (calculated by multiplying the single home load curve by the tariff) is comparable for the three different tariffs.

2.5. Algorithm

Fig. 6 shows a schematic representation of the algorithm utilised to control battery systems performing with the dynamic tariff. The optimum battery capacity for all the performance and economic indicators shown in Fig. 2 is calculated in this paper. This method could be useful for different stakeholders such us utility companies and end users to determine the preferred optimisation variable, e.g., self-sufficiency and levelised cost. The algorithm used the same logic for the three retail tariffs compared in this study and the battery system charges when PV generation was greater than the local demand load and vice versa. The difference for the different tariffs relies on the discharge, and the battery discharges when the SOC is greater than the minimum threshold and if (i) the demand of the single home is greater than PV electricity in the case of the simple tariff; (ii) local demand is greater than PV generating during the peak period for the double tariff; (iii) local demand is greater than PV electricity and the electricity price is higher than 0.25 CHF/kW h with the dynamic tariff according to Fig. 5. The price condition equal to 0.25 CHF/kW h was selected because this value is equal to electricity price during the peak period for the time-of-use tariff with two periods. Battery systems are only charged using local PV generation with the three different retail tariffs.

3. Results

Performance and economic results are presented for PbA and Li-ion technologies as a function of the battery capacity. Ten different battery capacities were compared for a single home, the largest capacity being equivalent to the maximum ES demand for PV energy time-shift i.e. the day of the year in which most surplus PV energy was available for storage. The battery capacity ranged between 2 kW h and 20 kW h which corresponds to 10% and 100% of the maximum ES demand respectively in the graphs below.

3.1. Performance results

Fig. 7 shows the PV_{ES}, SC_{ES}, η and equivalent full cycles for PbA and Li-ion batteries as a function of the battery capacity and the retail tariff. The PV_{ES}, SC_{ES} and η followed similar positive logarithmic trends and the positive slope decreased with the rising capacity, especially in the case of the round trip efficiency for Li-ion

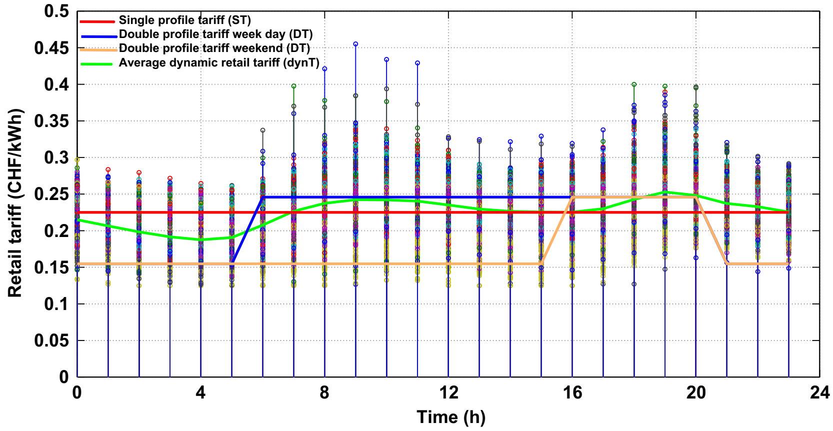

Fig. 5. Electricity prices for the single tariff (ST), double tariff (DT) and dynamic tariff (DynT) compared in this work. The single, double and dynamic tariff has one, two and 24 prices per day respectively. The dynamic tariff differs throughout the year while the single and double tariff offer the same profile for every day of the year. The data points represent the price fluctuations for the 8760 h of the year in 2015.

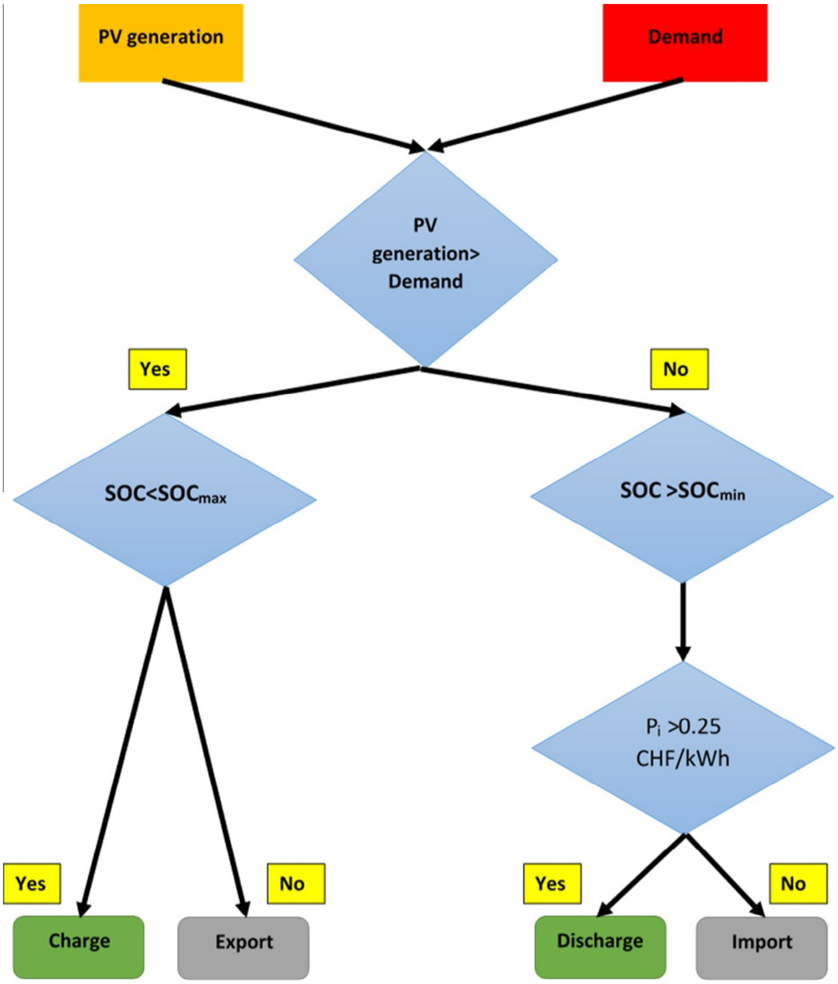

Fig. 6. Flowchart representing the algorithm which was utilised to obtain the performance of a battery system when performing PV energy time-shift with the dynamic tariff.

batteries. Compared to the simple tariff, battery systems stored less PV electricity under the double tariff and even less under the dynamic tariff, i.e. lower PV_{ES} and SC_{ES} were achieved. For example, a 12 kW h Li-ion battery system shifted 43%, 29% and 16% of the annual PV generation when performing with the simple, double and dynamic tariff respectively. The reason is that the control implemented for both the double and dynamic tariffs limited the battery discharge as explained above in Section 2.5. Likewise, the battery self-consumption decreased from 41% (single tariff) to 28% and 16% for the double and dynamic tariff respectively. Li-ion batteries achieved higher round trip efficiency values than PbA batteries although differences became smaller with increasing battery capacity. In order to illustrate this effect, the round trip efficiency of a 2 kW h and 20 kW h PbA battery system was equal

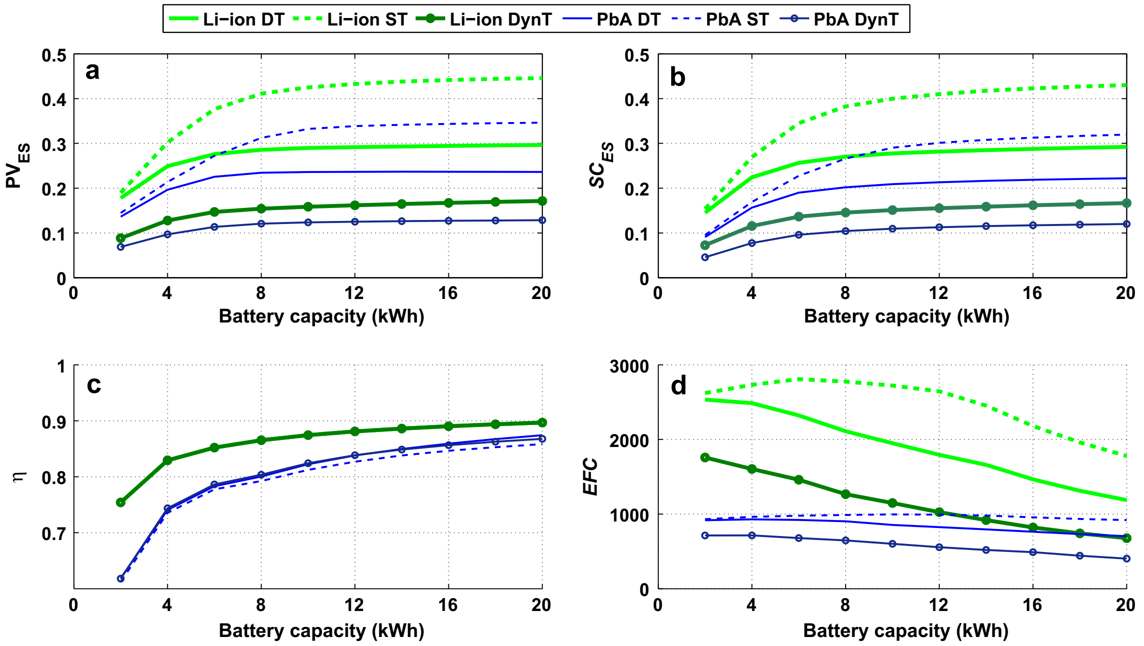

Fig. 7. Performance results of PbA and Li-ion batteries performing PV energy time-shift in a single home as a function of the battery capacity and retail tariff: (a) PV_{ES}, (b) SC_{ES}, (c) round trip efficiency and (d) equivalent full cycles.

Table 2
Performance and economic indcators optimised for PbA and Li-ion battery systems performing PV energy time-shift in a single home depending on the retail tariff. The battery capacity (kW h) which achieved the optimum values is shown in brackets.

Parameter (Unit)	PbA			Li-ion		
Tariff	ST	DT	DynT	ST	DT	DynT
PV_{ES}	0.35 (20)	0.24 (20)	0.17 (20)	0.45 (20)	0.30 (20)	0.17 (20)
SC_{ES}	0.32 (20)	0.22 (20)	0.12 (20)	0.43 (20)	0.29 (20)	0.17 (20)
η	0.86 (20)	0.87 (20)	0.87 (20)	0.90 (20)	0.90 (20)	0.90 (20)
EFC	996 (10)	930 (4)	715 (4)	2808 (6)	2535 (2)	1758 (2)
LCOES (CHF/kW h)	0.55 (16)	0.70 (12)	1.04 (4)	0.46 (8)	0.59 (6)	0.98 (6)
LVOES (CHF/kW h)	0.25 (20)	0.28 (20)	0.32 (20)	0.30 (20)	0.33 (20)	0.36 (20)
IRR (%)	−4.7 (20)	−5.0 (20)	−7.1 (16)	−0.2 (14)	−2.1 (14)	−5.0 (10)

to 61% and 86% respectively, reaching 75% and 90% respectively in the case of Li-ion technology. In addition to the higher round trip efficiency, the better capabilities of Li-ion batteries summarised in Table 1 including SOC range, discharge rating and durability also explain why Li-ion systems substantially achieved greater self-consumption. For example, a 12 kW h battery was able to meet 30% and 41% of the electrical demand load on an annual basis for PbA and Li-ion technology respectively.

Moreover, the pattern followed by the equivalent full cycles not only differed for the two battery technologies but it also changed depending on the chosen retail tariff for a given battery technology. The simple tariff did not limit the battery discharge and the equivalent full cycles increased to a maximum value with increasing capacity and then decreased. Beyond this maximum, increasing the capacity did not increase the equivalent full cycles because the capacity remained unused. Li-ion batteries required a smaller capacity to maximise the equivalent full cycles and the number of equivalent full cycles were markedly greater than those of PbA batteries. For example, the maximum number of equivalent full cycles were 2802 cycles and 996 cycles for a 6 kW h Li-ion and 10 kW h PbA battery respectively. This was related to the higher *SOC* range, discharge rating (shown in Table 1), durability and round trip efficiency of Li-ion batteries. The number of equivalent full cycles were lower and the pattern described above was less marked in the case of the other two tariffs which restricted the battery discharge according the electricity price value, this effect being more intense for the dynamic tariff and for Li-ion batteries. For the double and dynamic tariff, the maximum number of equivalent full cycles were achieved by the battery systems with the smallest capacity in the case of Li-ion technology, i.e. a 2 kW h Li-ion battery, specifically 2535 EFC and 1604 EFC respectively. In the case of PbA batteries, a 4 kW h battery achieved 917 EFC and 713 EFC with the double and dynamic tariff respectively, these values being the highest amongst all cases studied. The optimum performance results depending on the battery technology and retail tariff are compared in Table 2.

3.2. Economic results

Fig. 8 shows the *LCOES*, *LVOES* and *IRR* for PbA and Li-ion battery systems as a function of the battery capacity and the retail tariff. Despite its higher investment cost (the storage medium being 2.5 times higher compared to PbA batteries as reflected in Table 1), Li-ion battery systems offered lower *LCOES*, the minimum being equal to 0.46 CHF/kW h for a 8 kW h battery system performing with the simple tariff. For both battery technologies, there was an optimum battery capacity which minimised the *LCOES* of performing PV energy time-shift. This result was related to the

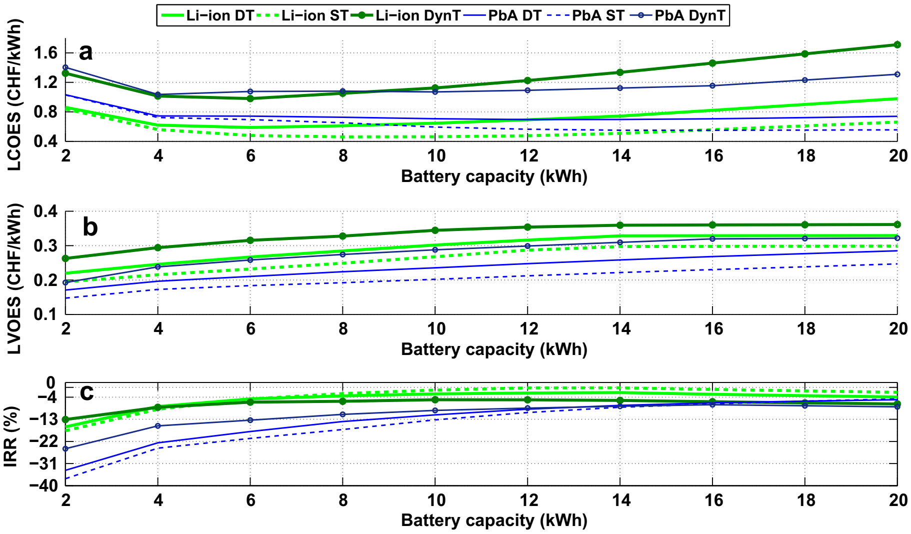

Fig. 8. (a) *LCOES*, (b) *LVOES* and (c) *IRR* for PbA and Li-ion batteries performing PV energy time-shift in a single home as a function of the battery capacity and retail tariff.

maximum number of equivalent full cycles and round trip efficiency values discussed above. Since PbA batteries required greater capacities to achieve high round trip efficiency values, the battery capacity which minimised the *LCOES* was significantly larger than that which maximised the equivalent full cycles, except for the dynamic tariff which limited the discharge and the optimum capacity as a result. As illustration, a 16 kW h PbA battery minimised the *LCOES* to 0.55 CHF/kW h while a 10 kW h capacity was required to maximise the equivalent full cycles as seen in the previous section. However, a 8 kW h Li-ion battery system minimised the *LCOES* (0.46) while a 6 kW h Li-ion battery system maximise the equivalent full cycles. The *LCOES* was smaller with the simple tariff: the investment cost for a given battery type and size is identical across the tariffs but the larger use (annual discharge) results in lower *LCOES* values for the simple tariff. For Li-ion technology, the minimum *LCOES* was equal to 0.59 CHF/kW h and 0.98 CHF/kW h with the double and dynamic tariff respectively.

The *LVOES* quantifies the value associated with the discharge and therefore the tariffs with minimum constraints for discharge achieved larger results as seen in Fig. 8. At the same time, the dynamic tariff reflects more accurately the real price of the electricity in the wholesale market and battery systems allowed to avoid the purchase of expensive electricity. Li-ion battery systems offered greater value than PbA batteries due to their higher round trip efficiency (since the revenue is linear to the round trip efficiency for PV energy time-shift) [17]. As shown in Fig. 8, the *LVOES* increases with battery capacity due to higher round trip efficiency and (especially) longer durability. Since retail electricity prices were assumed to increase by 5% p.a., battery systems with larger capacities were found to offer more value because they lasted longer. The highest *LVOES* was equal to 0.44 CHF/kW h and 0.40 CHF/kW h for a 20 kW h Li-ion and PbA battery system with the dynamic tariff respectively.

The *IRR* is the combined result of the value and cost offered by the investment. Li-ion batteries are a more profitable investment for any capacity and tariff but the results were found to be negative (i.e., not profitable) for both battery technologies regardless of the tariff. However, Li-ion batteries with a capacity of 12 kW h and 14 kW h performing with the simple tariff were able to achieve an *IRR* of −0.2%, this being the highest value (least negative), indicating nearly economic benefits for these capacities. However, these values were still significantly lower than the discount rate assumed in the baseline scenario (4%). An interesting finding to highlight is that PbA batteries with reduced capacities were more profitable when performing with the dynamic tariff than with the simple tariff. The reason was that these battery systems operate only for short periods per day (as a consequence of the price restriction related to this tariff) and cycle losses become less important as a consequence. This increased the durability of PbA batteries resulting in higher profitability in comparison with the other two tariffs. In the case of Li-ion technology, the simple tariff allowed batteries to manage more PV energy on a daily basis which increased the profitability. Only for very small capacities up to 4 kW h and 8 kW h with the dynamic and double tariff respectively, the *IRR* values achieved by Li-ion batteries were close to those for the simple tariff.

3.3. Alternative scenarios

Next to the reference cases three alternative scenarios were studied with the simple profile tariff (see Fig. 8). The first scenario focuses on the region of Jura where electricity prices are highest in Switzerland, namely 0.25 CHF/kW h in 2015 (as opposed to 0.225 CHF/kW h in Geneva). The second scenario analyses the same dwelling (including the same PV generation for the sake of simplicity and comparability) in the German economic context, i.e. for German wholesale (known as Phelix prices) and retail electricity prices. The day-ahead prices for Germany in 2013 according to the EPEX SPOT market [24] were utilised, the average wholesale price for Germany being 16% lower than for Switzerland. However, Germany is the EU country with the third highest retail prices for electricity after Denmark and Cyprus [51]. The average price in 2014 was equal to 0.35 CHF/kW h.

The third scenario addresses a fourth tariff designed to account for the ability of battery storage to smoothen the maximum power demand requested by an end user i.e. a capacity-based tariff. Capacity-based tariffs were already analysed by Jargstorf et al. who performed a detailed analysis on end-user reactions and the related grid upgrade costs, i.e. residential tariffs reflectivity [52]. According to the presented case study, a capacity tariff do not guarantee a final cost reduction for the distribution system operator but the user reaction could reduce upgrade cost when a capacity component on the PV injection is also added. The reduction of the maximum PV power exported to the grid is an important application for minimising the stress of PV generators on the distribution network system (beyond the self-consumption analysed in this study) but it requires dedicated battery schedules and forecasting methods in order to have available battery capacity when

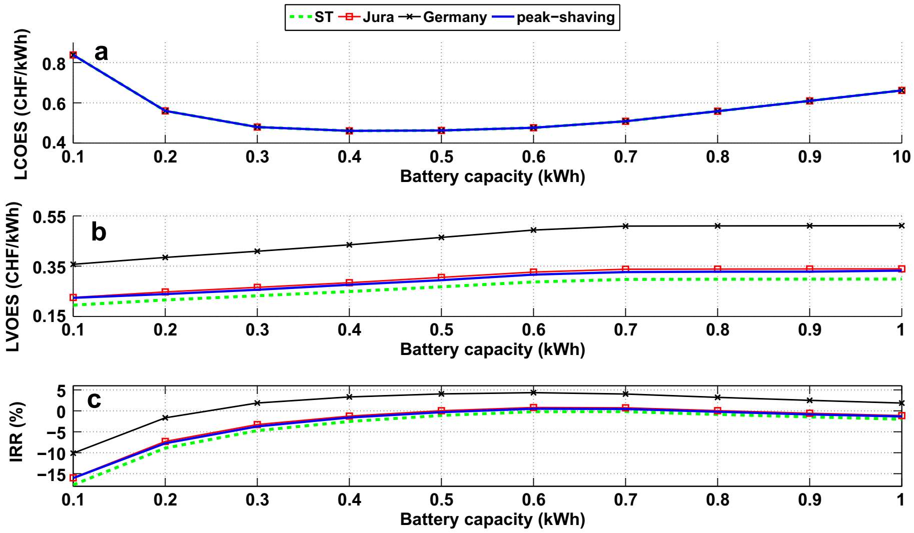

Fig. 9. (a) *LCOES*, (b) *LVOES* and (c) *IRR* for Li-ion batteries performing PV energy time-shift for three alternative scenarios in addition to the reference case for Geneva (Switzerland).

the maximum surplus PV power is available [52,53]. It should be noted that the four tariffs presented here do not remunerate the reduction of the maximum PV power exported to the grid but also the battery management is not optimised for this application.

At the moment, customers in Geneva with an annual demand larger than 30000 kW h/year are offered tariffs which integrates a power component (CHF/kW) in addition to an energy component (CHF/kW h). Although this tariff structure has not been utilised for small customers yet, there are several reasons why the extension of this approach to them may be suitable in the coming years. First of all, the peak demand load of single homes (and the global demand as a consequence) has increased over the last year due to the intensive use of electronic equipment, electrical cooking, etc., and it is expected to continue increasing due to the further penetration of heat pumps and electric drive vehicles. Also, the progressive use of smart meters which are able to record electricity consumption with high temporal resolution (equal or less than 1 h) will facilitate the inclusion of power components in tariffs. Finally, the diffusion of microgeneration systems in combination with local ES calls for the consideration of new value propositions which account for all the system benefits introduced by ES. According to this approach, the fourth tariff analysed in this study rewards the reduction of the maximum grid import with a rating equal to 8.1 CHF/(kW month) based on current tariffs for customer with an annual consumption higher than 30000 kW h/year [23]. This alternative tariff is referred to as "peak shaving" tariff. Li-ion battery systems performing with the simple profile tariff are being utilised to test these alternative scenarios since they obtained the best economic results (lower *LCOES* and higher *IRR*) in the baseline scenario. Technical performance results are not discussed for these alternative scenarios since the control of the battery system was not modified (the results of the economic analysis are hence indicative).

As shown in Fig. 9, the *LCOES* was the same for all cases because the different scenarios only impacted on the revenue of battery systems due to higher retail prices (Jura and Germany) or the addition of another ES application (peak-shaving). Using a battery system in the Jura region and Germany increases its value due to the higher retail prices compared to Geneva. Specifically, the maximum *LVOES* values achieved by the 20 kW h Li-ion battery were 0.34 CHF/kW h and 0.51 CHF/kW h, i.e. 13% and 70% higher than in Geneva. As a result, the profitability of Li-ion batteries increases and for Germany, *IRR* values for capacities ranging from 10 kW h to 14 kW h were greater than the assumed discount rate (4%) i.e., *LVOES* is greater than *LCOES*. The best result was found for a 12 kW h Li-ion battery which achieved *LCOES*, *LVOES* and *IRR* values equal to 0.48 CHF/kW h, 0.49 CHF/kW h and 4.3% respectively. The maximum *IRR* value decreased to 0.8% for a 12 kW h Li-ion battery in the Jura region since the *LVOES* only increased up to 0.34 CHF/kW h for this battery system. Alternatively, the consideration of peak-shaving made the economic results in Geneva similar to those in the Jura scenario. In other words, rewarding the shaving of the maximum grid import increased the *LVOES* by 10% and the *IRR* rose to 0.5%.

4. Sensitivity analysis

The robustness of the model utilised in this study and the accuracy of the results strongly depends on input data. Therefore sources of uncertainty in the input data should be considered in the analysis [54]. Similar to other studies discussed in the literature review above, local sensitivity analysis was the selected tool for tackling the different sources of uncertainty. By analogy with the ES modelling approach followed in this study, both parameters affecting the performance and economic benefits of battery systems were included in the sensitivity analysis. Specifically, the battery initial cost (including storage medium and inverter costs), the ageing due to cycle losses and the discount factor were considered for PbA and Li-ion battery systems operated with the simple and dynamic tariff. Likewise, the retail and wholesale prices were included in the sensitivity analysis for the simple tariff while the price condition was the selected parameter for the dynamic tariff. The sensitivity analysis was performed for the battery capacity for which the levelised cost was minimised depending on the battery technology and the tariff. The impact on the cost (*LCOES*), value (*LVOES*) and profitability (*IRR*) were assessed in all cases included. For all the sensitivity cases, the input data were varied between −30% and +30% of those selected for the baseline scenario with a resolution of 5%.

Fig. 10 shows that the *LCOES* is most sensitive to the initial cost, the relationship being linear with very similar slopes for PbA and Li-ion battery systems (0.48 and 0.44 respectively). Cycle losses are the second most influential parameter for the *LCOES* which

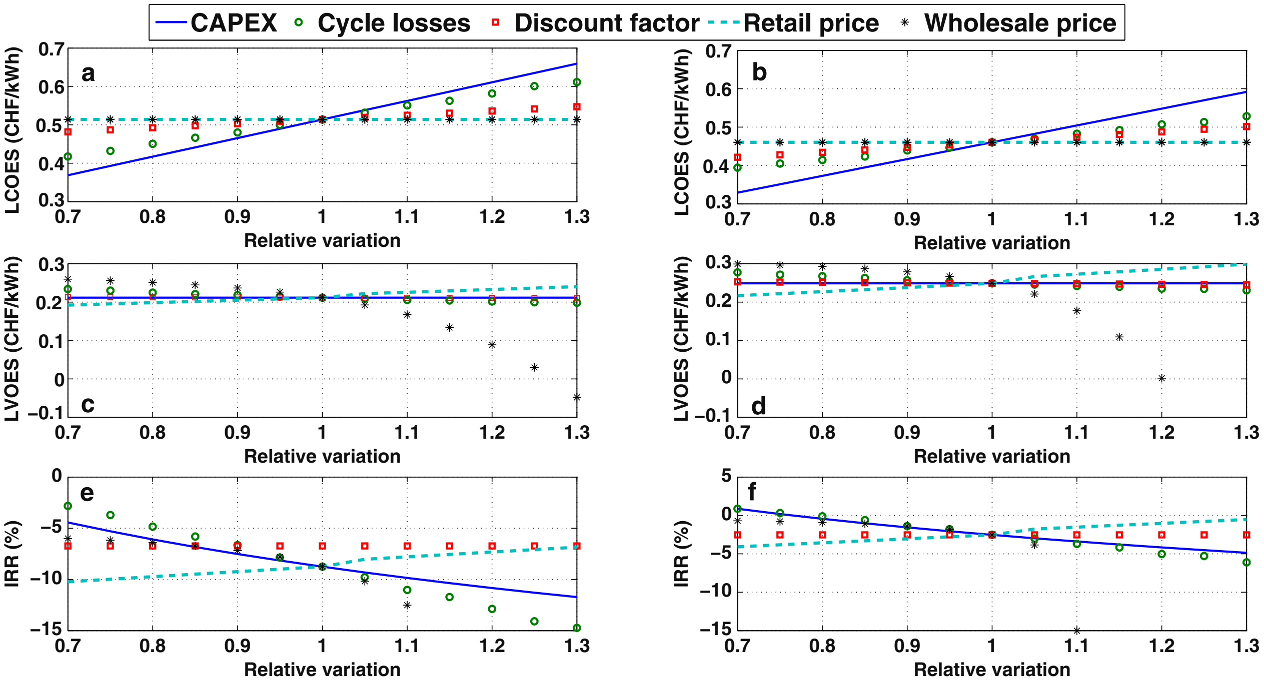

Fig. 10. (a) *LCOES*, (c) *LVOES* and (e) *IRR* of the optimum PbA battery system (16 kW h) and (b) *LCOES*, (d) *LVOES* and (f) *IRR* of the optimum Li-ion battery system (8 kW h) in combination with the simple tariff as a function of the battery initial cost, cycle losses, discount factor, retail price and wholesale price relative to the baseline scenario.

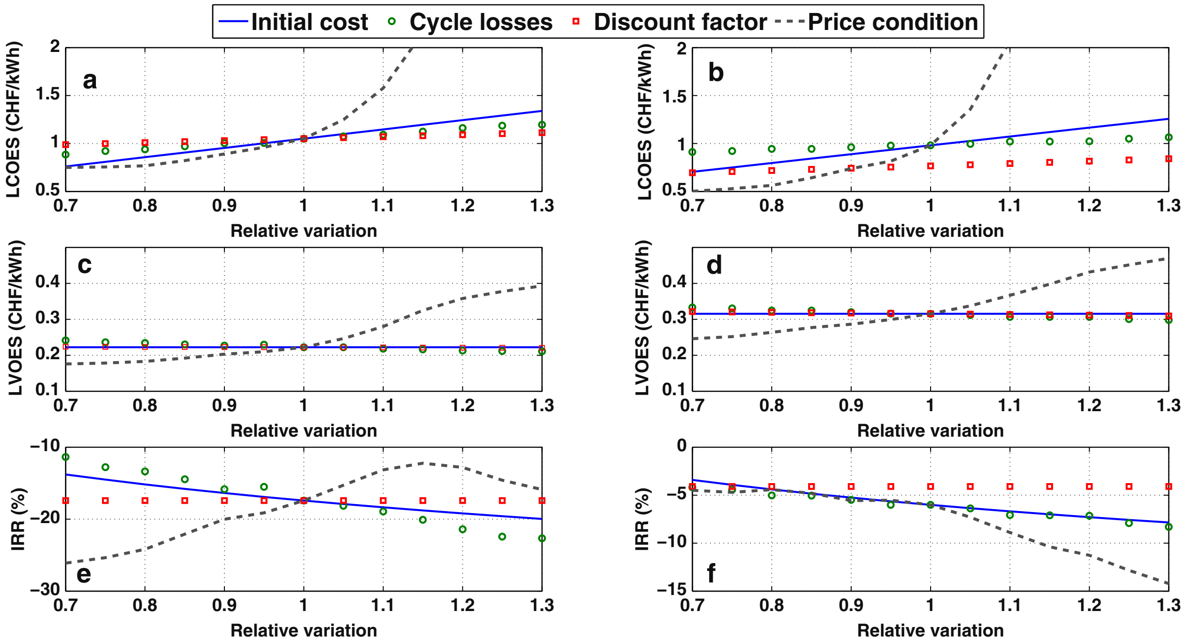

Fig. 11. (a) *LCOES*, (c) *LVOES* and (e) *IRR* of the optimum PbA battery system (10 kW h) and (b) *LCOES*, (d) *LVOES* and (f) *IRR* of the optimum Li-ion battery system (8 kW h) performing with the dynamic tariff as a function of the battery initial cost, cycle losses, discount factor and price condition for discharge regarding the input data selected for the baseline scenario.

decreased by 18% and 15% respectively when the cycle losses were assumed to be 30% lower than in the baseline scenario. The impact of the discount rate was much more limited and for a value of 2.8% (30% reduction), the *LCOES* decreased by only 9% from 0.46 CHF/kW h to 0.42 CHF/kW h for the Li-ion battery system. The *LVOES* was most sensitive to the wholesale prices and when these were assumed to increase by 20% on a yearly basis (while keeping the retail price constant), end users lost money with every discharge (negative *LVOES*), i.e. exporting electricity is more economically attractive than used it at home. When interpreting this result, the reader should bear in mind that, in reality, a retail price increase may also be driven by an increase in wholesale prices. If the retail price increases by 6.5% p.a. (30% increase), the *LVOES* would increase to 0.30 CHF/kW h (20% increase) for the 8 kW h Li-ion battery system. Finally, the *IRR* patterns were a combination of those followed by the *LCOES* and *LVOES*.

In the case of the dynamic tariff, Fig. 11 shows that the price condition for the battery to discharge has the largest influence on the three economic indicators. The *LCOES* increased asymptotically with the price condition (results for price conditions higher than 0.275 CHF/kW h are not shown). The *LVOES* also increased and it reached 0.39 CHF/kW h and 0.47 CHF/kW h for PbA and Li-ion batteries for a price condition of 0.325 CHF/kW h. The *IRR* followed different profiles for the two battery technologies. In the case of PbA battery systems, a higher price condition increased the durability of PbA battery systems and this was translated into higher *IRR* values, reaching a maximum of −12.2% for a price of 0.2875 CHF/kW h and it then decreased for higher price condition values. On the other hand, the *IRR* slightly decreases when the price condition increases from 17 CHF/kW h to 0.25 CHF/kW h and then decreases markedly for higher price condition values.

5. Discussion

Despite increasing the value of batteries by up to 28% compared to the simple tariff, the *IRR* values achieved by PbA and Li-ion batteries performing with the dynamic tariff were lower. Battery systems performing with the dual tariff offered an intermediate technical and economical performance. The simple tariff allowed battery systems to achieve the largest cycle activity throughout their lifetime and this increased the self-consumption as a result as shown in Fig. 7. The round trip efficiency was not influenced by the type of tariff and as a consequence the *LCOES* achieved with the simple tariff was markedly lower, with a minimum of 0.46 CHF/kW h for a 8 kW h Li-ion battery system.

As a consequence of the higher electricity prices, Li-ion battery systems were able to achieve positive *IRR* values in the Jura Region and in particular in Germany where a 12 kW h Li-ion battery was shown to be economically attractive i.e., the *IRR* (4.3%) was higher than the assumed discount rate (4%). The profitability values presented in this study for Germany are in range with those presented in two previous studies in which battery systems were found to be profitable in 2015 [5] and 2017 [13]. The economic results presented here are significantly better than those presented in a previous study for PbA battery systems in the UK by Mckenna et al. [14] where no economically viable case was found since results were based on retail electricity prices equivalent to 0.17 CHF/kW h and a PbA battery durability of less than 5 years. Additionally, a 12 kW h Li-ion battery also achieved a positive *IRR* in Geneva when the ability of battery systems to shave the maximum peak demand was rewarded (as it is done for large customers). Further benefits which battery systems could provide are reduction of the maximum PV power export peak, demand load shifting and ancillary services for the grid [8].

6. Conclusions

A time-dependent model has been used to analyse PV-coupled battery systems. Firstly, a dynamic tariff based on the wholesale market, i.e. one price per hour for every day of the year is compared with a flat rate and time-of-use tariff with two periods in Geneva (Switzerland) using PV generation and demand load with a temporal resolution of one minute. Secondly, the model simulated the variation of battery capacity, round trip efficiency and related annual discharge throughout the battery lifetime. This comprehensive techno-economic model allowed the comparison and optimisation of PbA and Li-ion battery systems accounting for the total cost (storage medium, inverter, balance-of-plant, maintenance) and battery ageing (including calendar and cycle losses).

The results demonstrated that simple retail tariffs (tariffs in which the electricity price is constant throughout the day) are the best option at the moment for end users who have PV-coupled battery systems which only perform PV energy time-shift. The reason for this is that battery systems are able to perform with a minimum levelised cost (0.44 CHF/kW h), i.e. managing more PV energy compared to a dynamic tariff. Additionally, Li-ion technology should be the preferred choice for PV-coupled battery systems even if the storage medium costs three times more than PbA technology; this is due to is capability for charging and discharging efficiently at high power rates even with limited battery capacity (less than 10 kW h). This conclusion relies on a Li-ion cycle life capability of 4000 equivalent full cycles. From a battery manufacturer perspective, technology characteristics including initial cost and durability were the most influential parameters for the levelised cost in addition to the price condition in the case of the dynamic tariff. A storage medium cost equal to 375 CHF/kW h, a durability of 5000 equivalent full cycles or a 6.5% retail price increase p.a. (based on a retail electricity price equal to 0.22 CHF/kW h in 2015) were necessary to achieve positive *IRR* values in Geneva.

Rewarding the reduction of the maximum grid import in Geneva (peak shaving) increased the levelised value by 10% and the *IRR* went up to 0.5%. According to this result, future value propositions for PV-coupled battery systems should consider the aggregation of benefits enabled by different ES applications. In this context, dynamic tariffs would not only reflect the wholesale market price (i.e. system fuel cost) by hour but also offer end users with a PV-coupled battery system the opportunity to benefit from battery discharges at high value (CHF/kW h). These novel value propositions should be designed by utility companies and supported by policy makers in order to promote battery storage as an enabling technology which brings several service, economic and strategic benefits to the energy system.

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