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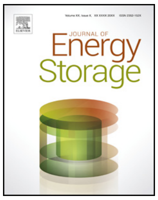

Optimizing PV and grid charging in combined applications to improve the profitability of residential batteries

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ABSTRACT

The energy storage market is growing exponentially and residential batteries are being deployed including in grid-connected housing, in order to increase on-site use of PV electricity, i.e. PV self-consumption. However, residential batteries have not reached economic profitability yet in most grid-connected situations, and alternative applications for residential batteries should be explored. This paper presents results from an economic optimization of the operation of a residential battery for two different applications, namely PV self-consumption and demand-load shifting under different dynamic tariff structures. A genetic algorithm was used to identify the optimal operation of the battery for both applications separately as well as combined, in order to investigate whether and under what circumstances the delivery of these two services can help to create an economic case. We find that the greatest monetary value per kWh of storage capacity installed is obtained when a battery is used for PV self-consumption under a single, flat tariff. Furthermore, adding demand-load shifting to the value proposition is economically attractive since it helps to minimize the levelized cost associated with battery storage. We also identify improvements needed for residential batteries to reach economic viability in Switzerland for both PV self-consumption and demand-load shifting, as for example, halving of capital expenditure of the battery system.

1. Introduction

1.1. Background

The cost of photovoltaic (PV) systems has dropped substantially thanks to economies of scale enabled by policies implemented across many countries since 2002 such as feed-in-tariffs (FiT), tax rebates and net metering [1,2]. In the domestic sector, more than 23 GW were installed worldwide in 2013, and installed capacity has grown by an average of 30% p.a. from 2013 through 2016 notably supported by the recent popularity of third-party leasing and tax credits [3]. The projected growth is more than 35 GW installed by 2018 [3]. In Switzerland, the number of PV system installations on single homes grew by 22.5% and 20.4% p. a. in 2014 and 2015 respectively [4].

Thanks to successful policies helping to bridge the gap to profitability and accelerating the deployment of PV systems, economic viability without incentives is being reached in some countries. In the US, states such as California, New York and Massachusetts have already achieved grid parity and in Europe, countries such as Germany, Italy, Spain and Denmark are approaching it. These countries have revised their FiT schemes, which are expected to be gradually phased out [6]. For example, Germany already reduced the FiT by almost half compared to 2010 (i.e., to 0.13 USD/kWh in 2015). The goal is to make a transition towards market integration of renewable energy (RE) without public support. In 2015 the Swiss FiT was between 0.17 USD/kWh and 0.19 USD/kWh for PV systems with a minimum installed capacity of 10 kW_p [7]. However, the PV penetration target and corresponding budget were reached that year and 36′700 installations ended up on the waiting list to benefit from the FiT. Those installations on the waiting list and with capacities between 2 and 10 kW_p, have the option to sell their electricity to the local utility at a yearly fixed tariff plus a premium, in Geneva at the moment 0.049 USD/kWh and 0.054 USD/kWh respectively.

The decline in the value of FiT together with the increase of electricity prices over the last years have ended the high profitability of investments in PV in countries such as Germany, Italy and Spain (e.g., the FiT was by 0.21 USD/kWh larger than the electricity price in Germany in 2009 while it was by 0.17 USD/kWh

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Nomenclature

CAPEX	Capital expenditure
DT	Double tariff
DynT	Dynamic tariff
EFC	Equivalent full cycles
FiT	Feed-in-Tariffs
FT	Flat tariff
GAL	Genetic algorithm
LCOES	Levelized cost of the ES
LVOES	Levelized value of the ES
NPV	Net present value
O&M	Operation and maintenance
PV	Photovoltaic
RE	Renewable energy
SOC	State of charge
TOU	Time of use
TSC	Total self-consumption

lower than the electricity price in 2014). This trend makes PV self-consumption more attractive and profitable without subsidies. PV self-consumption indeed allows the consumer to save money by using local PV generation rather than buying electricity from the grid, since the cost per kWh of self-generated renewable electricity is equal or lower than the electricity imported from the grid. At the system level, lower distribution losses and peak demand reduction by increased self-consumption are other benefits which could potentially contribute to the energy transition.

In this context, batteries can be used to increase the share of PV self-consumption and reduce the electricity bill [10–12] (see Fig. 1), as reported by Luthander et al. who performed a review of studies on PV self-consumption in residential buildings [8]. Battery storage was found to increase self-consumption by 13 to 24% with a power capacity ranging from half the installed PV peak power to parity. The technological and economic performance of PbA batteries and hydrogen storage were compared for a single house in the UK by Parra et al. [11]. They concluded that battery technology is more suitable than hydrogen to perform PV self-consumption based on daily basis due to higher round-trip efficiency and negligible self-discharge. Lithium-ion (Li-ion) is at the moment the benchmark technology for PV self-consumption due to high energy density, power density and conversion efficiency (80–90%) [12,13]. For example, more than 90% of the residential batteries installed in Germany in 2015 were Li-ion according to the latest data from the German federal program [14]. The current price per usable capacity of Li-ion Phosphate batteries is between 500 and 1500 USD/kWh and the price for lithium-nickel-manganese-cobalt technology is close to 510 USD/kWh [15]. Despite these values, the profitability of PV-coupled battery systems has not been reached yet, i.e. the achieved overall reduction in electricity bill over the lifetime of the battery does not fully recover the battery investment [15–17].

In addition to battery cost reductions, economic viability may be reached by providing multiple services [19].Besides increasing PV self-consumption, batteries can also perform demand-load shifting which consists of charging the battery with cheap grid electricity at off-peak time and discharging it during peak time (typically in the evening) as shown in Fig. 2 [20].

1.2. Literature review

The following literature review is divided into optimization techniques for PV self-consumption, demand-load shifting and both applications combined according to the applications addressed in this study.

1.2.1. PV self-consumption optimization

Moshövel et al. compared strategies for maximizing PV self-consumption in Germany based on weather and load forecast and using a proportional-integer controller to adjust the cut-off limit [21]. It was found that the accuracy of weather forecast is crucial to relieve the grid use and that a storage system managed with a forecast algorithm has a significantly higher potential to reduce the grid load compared to a system that only maximizes PV self-consumption. Riffonneau et al. proposed power management optimization using dynamic programming [20]. The study was carried in France, using a French standard electricity price. A day-ahead approach of power management for PbA batteries was used. However, the economic viability of installing a battery was not studied. Parra and Patel used a simulation-based approach with an algorithm with SOC as threshold trigger for determining the optimum PV-coupled battery system in terms of technology (PbA

Fig. 1. Electricity balance of a dwelling with a PV-coupled battery system performing PV self-consumption for one representative day as well as the state of charge (SOC) of the battery. The electricity flows to meet the demand load, PV generation, battery discharge and grid import are shown as negative values. Battery charge and grid export are shown as positive values.

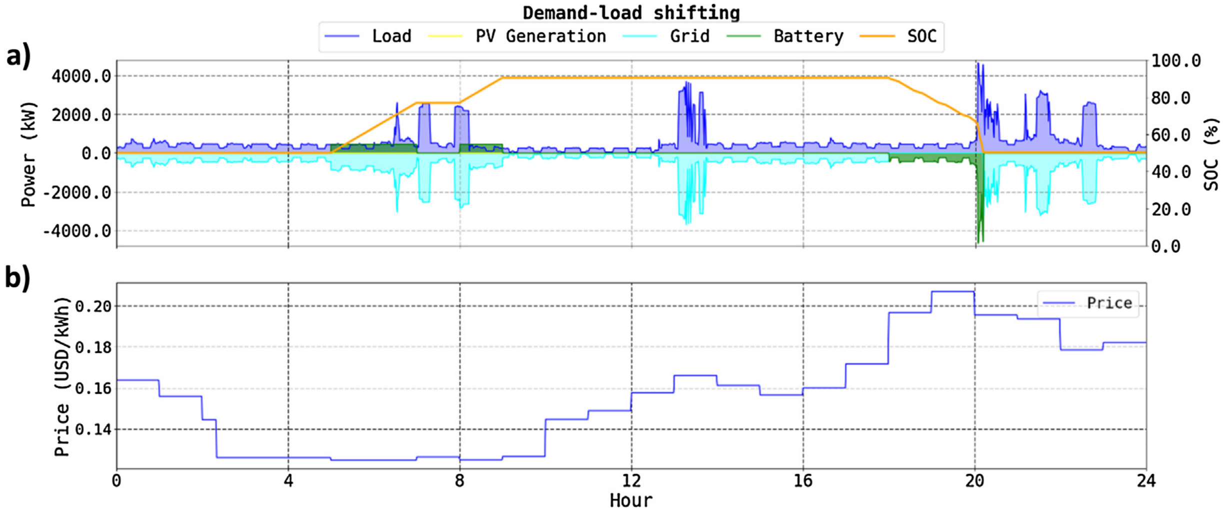

Fig. 2. a) Electricity balance for a dwelling with a battery system performing demand-load shifting for one representative day as well as the state of charge (SOC) of the battery. The electricity flows to meet the demand load, battery discharge and grid import are shown as negative values. Battery charge is shown as positive values. b) Electricity prices using a dynamic tariff for one representative day.

versus Li-ion), battery capacity and three different retail tariff in Geneva, Switzerland [16]. The results indicated that a simple retail tariff (i.e. constant electricity price) maximizes PV self-consumption because of the larger number of cycles throughout battery lifetime. Li-ion battery technology was found to be preferable for such an application due to its capability to efficiently charge and discharge at high power rates. Nonetheless, none of both battery technologies achieved economic viability in Switzerland.

1.2.2. Demand-load shifting

Demand-load shifting has been less discussed in the literature since PV self-consumption is the primary application for residential batteries. Demand-load shifting can, for example, be implemented by dynamic programming of a battery, as presented by Yoon and Kim [10]. They used scenarios with and without solar power as well as 5 different types of Time-of-use (ToU) tariffs and a day-ahead dynamic tariff in the US. Zheng et al. found that a 30 kWh battery can offer annual savings of 700 USD under a residential ToU tariff when compared to a scenario without battery [18]. Assuming the Tesla PowerWall® characteristics, Davis and Hiralal analyzed the rate of return associated with a battery used to minimize demand peak loads in the UK [17]. They concluded that under current UK policy conditions, batteries for demand-load shifting are currently not an attractive investment for households and proposed a payment from the government for every kWh of peak electricity demand displaced due to grid benefits such as CO_2 emission reductions and deferral of investment in new power plants to replace decommissioned ones.

1.2.3. Combining applications

In addition to technological improvement and cost reduction, combined applications (or services) are becoming increasingly relevant for residential battery deployment. At a micro-grid scale, Chen et al. developed a smart energy management system using a genetic algorithm (GA) to minimize operational costs including both PV and grid charging, but the gradual change of key parameters over the lifetime of the battery was not included in the study [22]. Nottrott et al. focused on peak shaving through a medium scale PV-coupled battery system using a ToU electricity rate [23]. They found an increase of the net present value (NPV) compared to predefined dispatch strategies, however, without analyzing the role of the various parameters in a sensitivity analysis. Focusing on residential scale, Yoon and Kim used a GA to optimize the battery schedule, charging from the grid during off-peak periods, and from the PV-array in case of surplus, to reduce the electricity bill [9]. Nevertheless, the analysis did not consider the battery efficiency or the capital cost of the battery. Ratnam et al. aimed to maintain grid voltage within acceptable limits for residential PV systems maximizing the financial benefit associated with the daily battery schedule, leaving out life-cycle considerations [24]. In conclusion, combined applications have not yet been explored in depth for residential batteries.

1.3. Objective of this study

According to the literature review presented above, an in-depth analysis of the trade-offs between PV self-consumption and demand-load shifting applications has not been published to date. Furthermore, the gradual change of key parameters over the lifetime of the battery has not been thoroughly studied when combining applications. Acknowledging the high price of batteries, we perform a techno-economic analysis to investigate if and under what conditions batteries performing both PV self-consumption and demand-load shifting simultaneously help to create an economic case for residential batteries. In order to do so, we first optimize the operation of the battery (scheduling) and compare results for different sizes of Li-ion batteries performing PV self-consumption and demand-load shifting separately and under different dynamic tariff structure. Secondly, we optimize operation of different sizes of Li-ion batteries delivering both services. The study assumes the pre-existence of a PV system; therefore, we focus on the techno-economic implications of adding a battery system to the PV system and we evaluate the trade-offs of stacking demand-load shifting to PV self-consumption (the cost of the PV system is hence not taken into account).

2. Data and method

Following the general logic of our modeling approach depicted in Fig. 3, the technological and economic input parameters of the

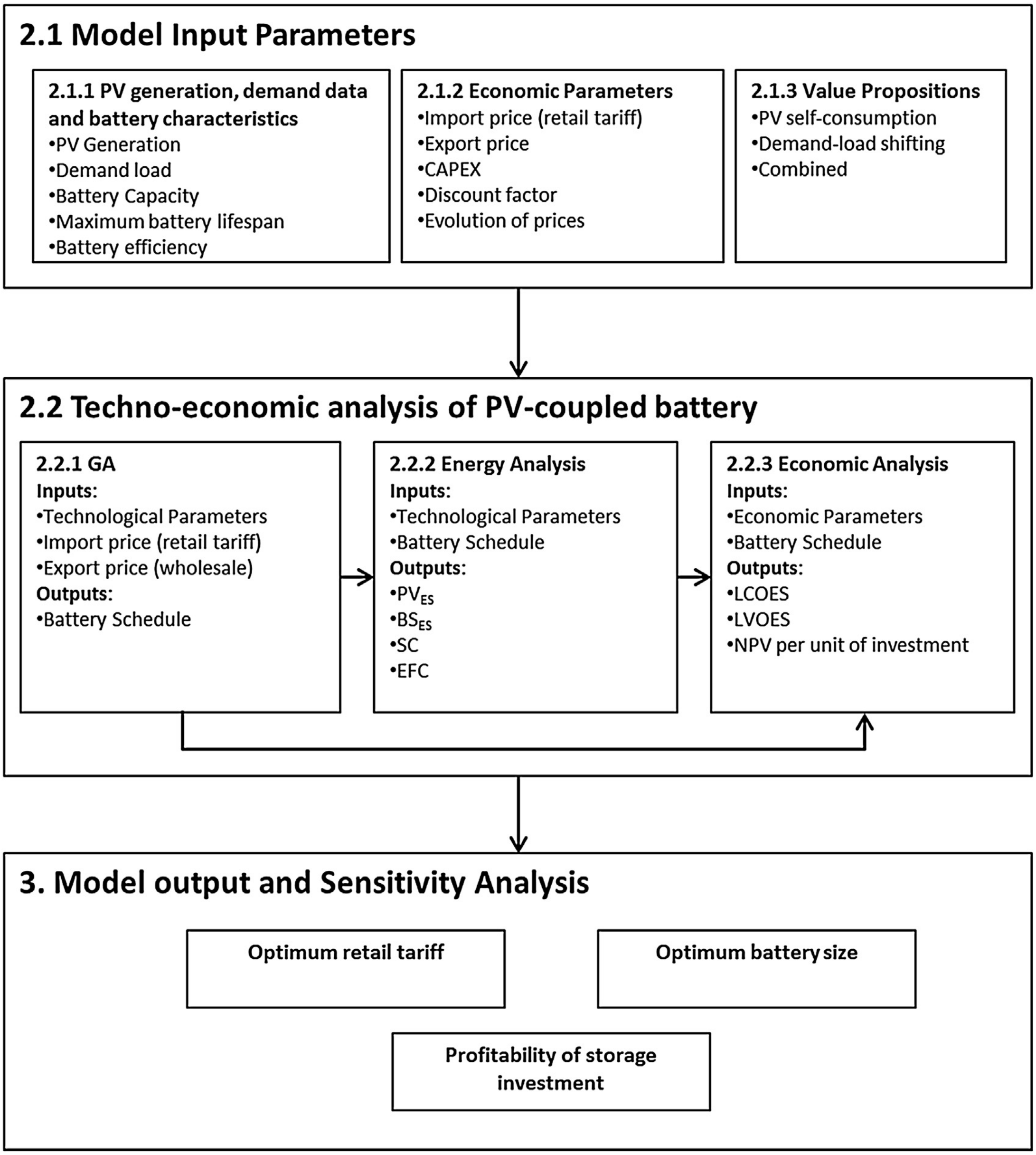

Fig. 3. Overview of the proposed model structure.

model are presented in the subsequent sections, including the three retail price scenarios as well as the three application scenarios considered.

2.1. PV generation, demand data and battery characteristics

We use both electricity demand and PV generation monitored in 2013 in a single-family house in Neuchâtel (Switzerland) inhabited by a 5-person family. The annual electricity consumption is 4950 kWh. Electricity was generated on-site with a 5 kW_p PV-system using Micromorph modules with a 30° south orientation [25]. We aggregated the original 1-min resolution data to 1-h resolution in accordance with our hourly day-ahead forecast. Concerning the battery technology, Li-ion batteries with capacities ranging from 1 kWh to 10 kWh are considered for this study based on results from previous battery studies in Europe [26], as well as the current availability of batteries in the local market (typically between 2 kWh and 10 kWh) [27]. The various battery parameters included in the model are presented in Table 1. The maximum calendar lifetime is assumed to be 15 years. The SOC at a given point in time is the percentage of the battery total energy capacity that is still available to discharge. For optimal durability, the SOC must remain between maximum and minimum limits given in Table 2. The maximum discharge and charge rating are set to the double of the nominal capacity ($2C_{nom}$) in accordance with current Li-ion characteristics, but these ratings are in any case limited by the inverter capacity (3.5 kW for the larger capacities).

2.2. Economic parameters

The performance of Li-ion batteries is compared under three types of retail tariff structures (see Fig. 4) a flat tariff (FT), a double tariff (DT) and a dynamic tariff (DynT) with the price varying on an hourly basis. The first two cases represent tariffs implemented by the power and gas utility 'Services Industriels de Genève' (SIG) in Geneva (Switzerland). The value of the FT is 0.25 USD/kWh for every hour of the year. The DT is divided in peak and off-peak hours, with prices being 0.27 and 0.17 USD/kWh respectively. The

Table 1
Technical and economic characteristics assumed for Li-ion batteries in this study. Those parameters included in the sensitivity analysis are in bold.

Parameter (Unit)	Value	Parameter (Unit)	Value
Round trip Efficiency	0.9	Storage medium cost (USD/kWh) [b]	**450**
Maximum charge rate (A/h)	2*C	Inverter Cost (USD/kW) [b]	**540**
Maximum discharge rate (A/h)	2*C	Balance of plant cost (USD/kW)[b]	**100**
ΔSOC	0.8	O&M (USD/kW)	10
Maximum SOC	0.9	Export price (USD/kWh)[c]	**0.0559 (±30%)**
Minimum SOC	0.1	Discount rate[d]	**4% (±30%)**
Maximum cycle life (EFC)	**4000(±30%)**	Retail price increase p.a.	**2% (±30%)**
Lifetime (years)[a]	**15 (±30%)**		

[a] From available literature [14,16,25,28].
[b] Included in CAPEX.
[c] Wholesale electricity price in Switzerland [16].
[d] Social discount factor in agreement with [13,16,28].

off-peak hours occur from 10 pm to 7 am during the week and 10 pm to 5 pm over the weekend, all year round. Similar 2-period ToU tariffs are available in other countries such as the UK and France. The data for the DynT is based on the wholesale 2013 market prices in Switzerland and includes network usage, community services and RE incentives; also the FT and the DT include these components [16]. The DynT prices range from 0.12 to 0.46 USD/kWh. We assume a 2% p.a. increase of electricity prices in the baseline scenario and in accordance with the projections used by the Swiss Federal Office [28,29]. Regarding the PV export price, it was assumed that PV generators sell electricity to the wholesale market, as other generators do. As a simplification, we assume the export price to be constant and equal to the average wholesale electricity price from the day-ahead market for Switzerland in 2013, 0.06 USD/kWh [16]. This value was kept constant with time in the baseline scenario based on a wholesale price projection until 2020 from the European Energy Exchange [30]. These various parameters are finally included in the sensitivity analysis.

The capital expenditure (CAPEX) includes the battery (storage medium), balance of plant and inverter costs. The inverter rating is fixed, i.e. 3.5 kW in agreement with typical commercialized products for the battery capacity range considered (e.g. SE3500 from Solar Edge, compatible with Tesla Powerwall and LG Chem RESU), with the exception of the 1 kWh battery since in this case the maximum discharge rate requires a capacity of only 2 kW. For the economic analysis, we assume a social discount rate of 4% in agreement with previous studies (e.g. [16] and [31]), and assuming that the owner of a PV installation is nowadays keen on increasing the amount of local PV self-consumption. Table 1 shows the values considered for the different CAPEX components. Since new battery models available in the market do not require any regular maintenance, it is assumed that a fee for any unexpected maintenance is paid when the battery is purchased.

2.3. Value propositions

Three different value propositions in terms of type and number of applications are compared in order to understand the techno-economic performance of Li-ion batteries with different charging conditions. We consider PV self-consumption in the first instance, where the battery is used so as to increase the share of on-site PV generated electricity in meeting the load. We then focus on demand-load shifting under variable prices. This application is always combined with dynamic tariff structures (see Eqs. (15) and (17)). The last value proposition combines the two previous cases, with the objective of identifying whether combined services improve the economic performance of residential batteries. Fig. 5 shows a schematic representation of a residential battery system for the three value propositions, including the various supply sources. Based on the combination of the three different retail prices and three value propositions, seven scenarios are defined, as displayed in Table 2.

Table 2
Scenarios for residential batteries compared in this study, depending on the value proposition and tariff considered.

Scenario	Value proposition	Tariff
1	PV self-consumption optimization	Double
2	Combined	Double
3	Demand-load shifting	Double
4	PV self-consumption optimization	Dynamic
5	Combined	Dynamic
6	Demand-load shifting	Dynamic
7	PV self-consumption optimization	Flat

2.4. Techno-economic analysis of residential batteries

The optimal battery schedule is defined as the one that minimizes the electricity bill of the dwelling. Therefore, it varies as a function of the value proposition and type of retail price. For PV self-consumption, the optimal scheduling depends on the ratio between PV electricity export price and grid electricity import price (see Eq. (15)). With the flat and double tariffs, the battery operation has already been formulated as a linear programming problem for example by Yoon and Kim [9]. One of our scenarios, however, includes a dynamic tariff with prices varying on an hourly basis throughout the day. This dynamic aspect leads to a non-linear objective function for which optimization cannot be solved with linear programming algorithms. Methods such as dynamic programming, nonlinear programming or heuristic algorithms must be used to solve the problem [10]. In this study, we decide to use GA as optimization technique because it requires less computing time than combinatorial optimization algorithms such as dynamic programming and allows to use more variables to be considered within the optimization. GA has been applied for modeling hybrid RE systems while it has been scarcely used in battery scheduling [32]. For the optimization, we considered the following assumptions:

- 24 h optimization framework, i.e. one full day is optimized at a time and this is repeated for each day of the year.
- Perfect day-ahead forecast of the residential load and solar PV generation in order to determine the maximum economic potential regardless of the forecast strategy used.
- Electricity prices are known on a day-ahead basis regardless of the retail tariff.
- Batteries do not export electricity to the grid since there is no economic incentive for it from the perspective of a consumer (i.e. the import price is at least three times greater than the export

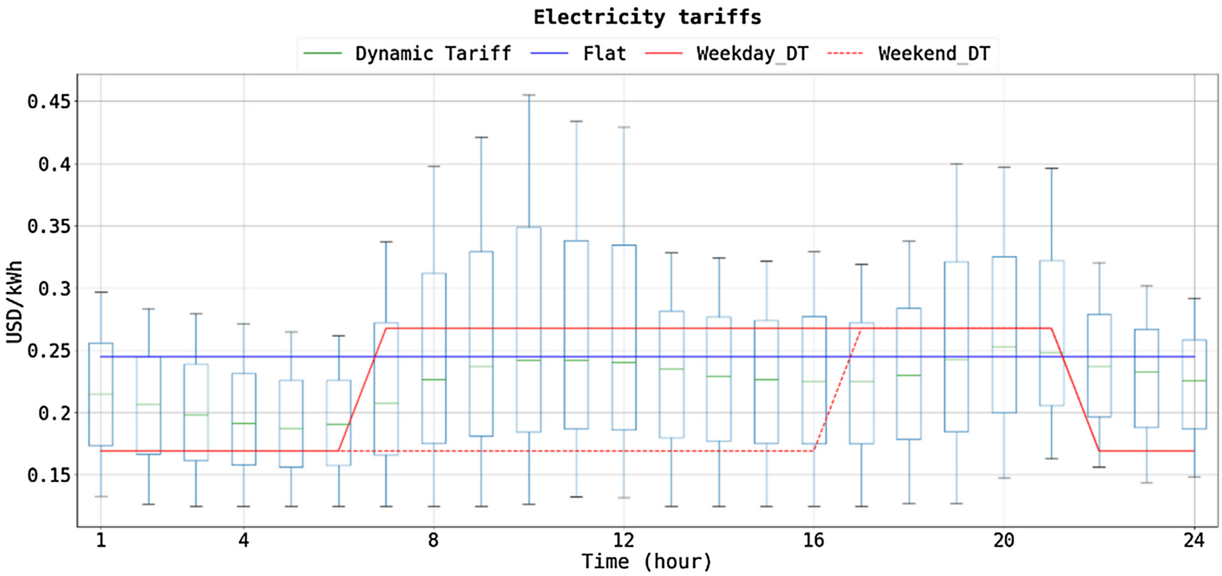

Fig. 4. Electricity prices for the flat tariff (FT), double tariff (DT) and dynamic tariff (DynT) used in this work. The single, double and dynamic tariff have one, two and 24 prices per day respectively. The electricity price of the dynamic tariff differs throughout the year and this figure also provides the maximum, minimum and average prices. The duration of the peak period is shorter during the weekend for the double tariff but the same weekly profile is repeated throughout the year. Finally, the price is constant throughout the year for the flat tariff.

price in the case of the dynamic tariff and four times in the case of the double tariff).

The objective function is the minimization of the daily electricity bill, defined in Eq. (1), with the hourly battery schedule (charge or discharge) and the battery capacity being chosen as the independent variables. The PV system is not part of the optimization problem since we consider an existing PV system and the investment decision here considers the viability of adding a storage system to it. The maximum charge and discharge rates are defined by Eqs. (8) and (9). The battery capacity is an integer variable within the range of 1 to 10 kWh, with values equal to natural numbers. The constraints of the optimization problem vary depending on the applications and tariffs selected. Some constraints are imposed in order to ensure that battery operation is safe and the final durability is not affected (Eqs. (7)–(10)); Eq. (10) is related to the assumption that the battery is fully discharged on a daily basis and the SOC is set at half $\mathrm{SOC_{max}}$ at the end of the day allowing for some operational flexibility for the next day. Eq. (11) restrains the battery from exporting electricity to the grid, preventing $\mathrm{w_i}$ to be equal or greater than the amount of PV-generated energy at the time *i*, i.e. the electricity supplied to the grid cannot be greater than the PV-generated energy. These restrictions are common to all scenarios, while Eqs. (12) and (13) may vary according to the application and retail tariff. Supplementary information on the model equations can be found in supplement Section A.

$$\boldsymbol{Min}\sum_{i=1}^{T}\left(\left(\boldsymbol{I}(\boldsymbol{w_i}>0)*\boldsymbol{P_{import\ i}}+\boldsymbol{I}(\boldsymbol{w_i}\le 0)*\boldsymbol{P_{export\ i}}\right)*\boldsymbol{w_i}\right) \tag{1}$$

Where:

$$w_i = E_{char\ i} + E_{dis\ i} + l_i - g_i \tag{2}$$

$$E_{char\ i} = x_i\ if\ x_i > 0 \tag{3}$$

$$E_{char\ i} = 0\ if\ x_i \le 0 \tag{4}$$

$$E_{dis\ i} = x_i * \eta\ if\ x_i \le 0 \tag{5}$$

$$E_{dis\ i} = 0\ if\ x_i > 0 \tag{6}$$

Subject to:

$$SOC_{min} < SOC_0 + \sum\nolimits_{i=1}^{T}(x_i) < SOC_{max} \tag{7}$$

$$|x_i| < P\_max\_dis \tag{8}$$

$$|\mathrm{x_i}| < P\_max\_char \tag{9}$$

$$x_1 = x_{24} = \frac{SOC_{max}}{2} \tag{10}$$

$$w_i \ge -g_i\ \ if\ \ w_i \le 0, \forall i \tag{11}$$

$$x_i \le 0\ \ if\ \ \eta < \frac{\max(P_{export})}{min(P_{import})} \tag{12}$$

$$x_i > 0\ \ if\ \ \eta \ge \frac{\max(P_{export})}{min(P_{import})} \tag{13}$$

Across the equations above, *i* is the hour of the day, w_i (kWh) is the electricity drawn from ($w_i > 0$) or supplied to the grid ($w_i \le 0$) (kWh). x_i (kWh) is the electricity discharged from (negative) or fed to (positive) the battery at the hour *i* of the day and it is separated in two vectors (Eqs. (3)–(6)), with $E_{char,i}$ (kWh) being the electricity supplied to the battery and $E_{dis,i}$ (kWh) the electricity discharged by the battery; l_i (kWh) is the demand-load; g_i (kWh) refers to the PV generation; P_{import} (USD/kWh) is the electricity (import) price at which the battery is discharged and P_{export}(USD/

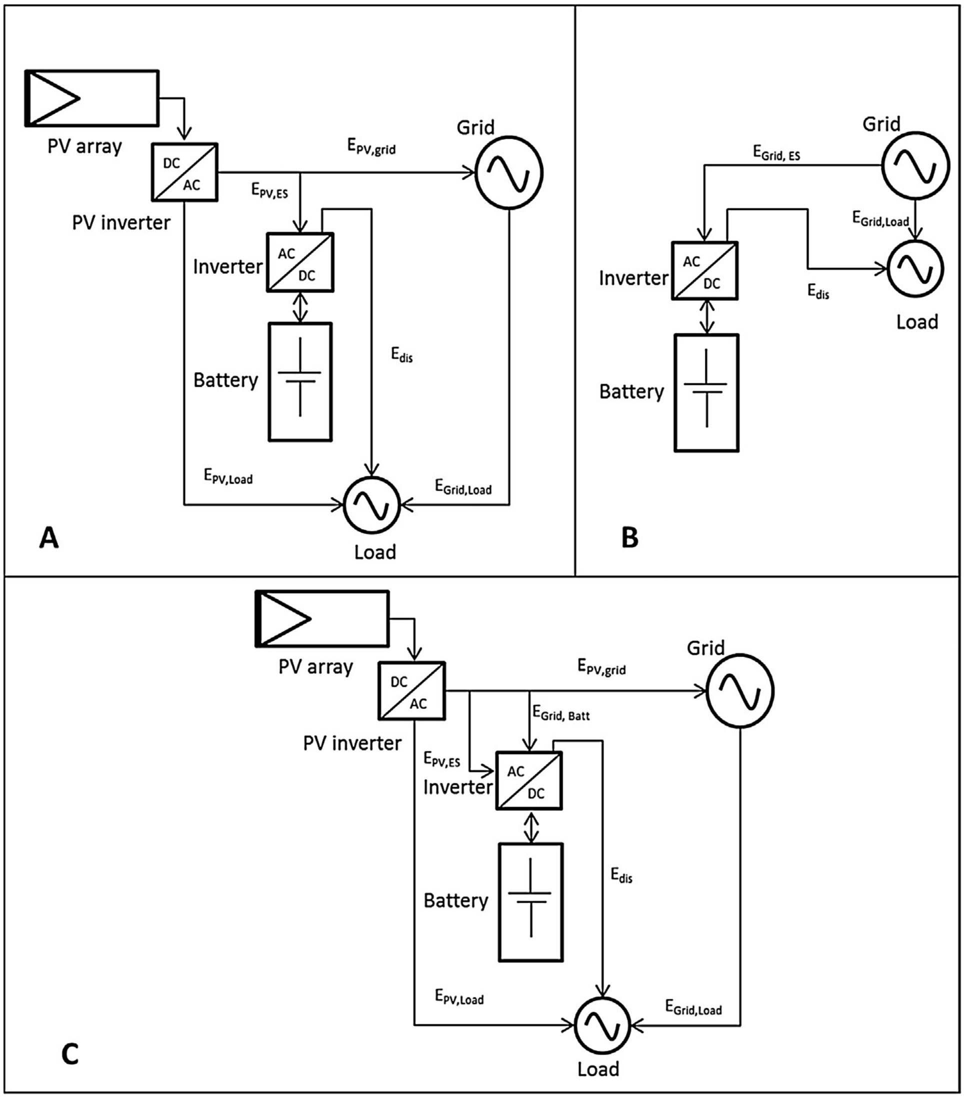

Fig. 5. Schematic representations of the battery system for the three value propositions compared in this study: A) PV self-consumption, B) demand-load shifting, C) Combined applications.

kWh) is the price at which the battery is charged, i.e. when the battery is charged from the PV system is the PV export price. $I(w)$ is the indicator function that is 1 when the statement is true and 0 when is false. $SOC_{\min}$ and $SOC_{\max}$ are the minimum and maximum SOC respectively (see Table 1). $SOC_0 + \sum_{i=1}^{T}(x_i)$ refers to the battery SOC at time i, with SOC_0 being the SOC at the beginning of the day. T is the period of time for the optimization, i.e. 24 h. $P\_\max\_\text{dis}$ and $P\_\max\_char$ (A/h) are the maximum battery discharge and charge rate respectively and η is the battery round trip efficiency.

Eq. (14) represents the daily revenue for PV self-consumption. Eq. (15) is a condition, derived from Eq. (14), which stipulates the minimum round trip efficiency of the battery system for performing PV self-consumption as a function of the ratio between the PV export and import prices. Likewise, Eqs. (16) and (17) give the condition for demand-load shifting. Eq. (17) specifies that the battery should only be charged if the round-trip efficiency is higher than the ratio between the off-peak and peak prices. When PV self-consumption and demand-load shifting are performed simultaneously, the algorithm chooses between the two set of equations according to the PV electricity generated, i.e. Eqs. (14) and (15) are used whenever PV generates electricity while Eqs. (14) and (15) are used in all other periods.

$$Rev = \sum_{t=1}^{24}(E_{dis\ i} * P_{import\ i} - E_{char\ i} * P_{export\ i}) \tag{14}$$

$$\eta - \frac{\max(P_{export\ \ i})}{\min(P_{import\ \ i})} \geq 0 \tag{15}$$

$$Rev = \sum_{t=1}^{24}(E_{dis\ i} * P_{peak\ i} - E_{char\ i} * P_{off-peak\ i}) \tag{16}$$

$$\eta - \frac{\max(P_{off-peak\ \ i})}{\min(P_{peak\ \ i})} \geq 0 \tag{17}$$

2.4.1. Genetic algorithm[1]

GAs have been used in many battery size optimization studies. For

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[1] For further information see supplement Section B.

example, Magnor and Sauer developed a modular simulation model integrated into a GA framework to optimize the levelized cost of electricity for various PV and battery configurations without battery scheduling optimization [33]. They compared current economic scenarios with and without policy support, and found a levelized cost of the optimal system (PV and battery system) of 0.23 USD/kWh and a break-even battery price of 580 USD/kWh for new PV-coupled battery systems. Chen et al. presented a smart energy management system to optimize the operation of a micro-grid for demand-load management with a GA [22]. To the best of our knowledge, the only previous study which proposed a GA for optimizing the schedule of a battery was presented by Yoon and Kim [9].

In this study, the proposed GA minimizes the daily electricity bill through battery scheduling, defined by Eq. (1). It was implemented using MATLAB® and its GA function capability. It consists of an initial population of 100 "chromosomes" and it terminates when no significant progress is made or after 1000 generations. A permutation encoding has been done for this GA, where every chromosome is a string of numbers. We used the fitness proportionate selection method which grants candidate solutions a higher fitness value, thereby bringing down probability to be eliminated, although this cannot be fully dismissed. A scattered crossover function was used with the offspring fraction set to 0.8. Finally, a Gaussian mutation was used. The parameters were tuned by balancing execution time and premature convergence. The main algorithm flow chart is presented in Fig. 6, additional flow charts can be found in supplement Section C. On the other hand, supplement Section D presents the algorithm validation. The simulation of one day takes around 18 s.

2.4.2. Technical performance indicators

Three indicators were adopted to evaluate the performance of Li-ion batteries and their impact on the household energy balance depending on the applications performed, the retail tariff and the battery capacity: First, the total self-consumption (TSC) is mathematically defined in Eq. (18) as the ratio of the amount of

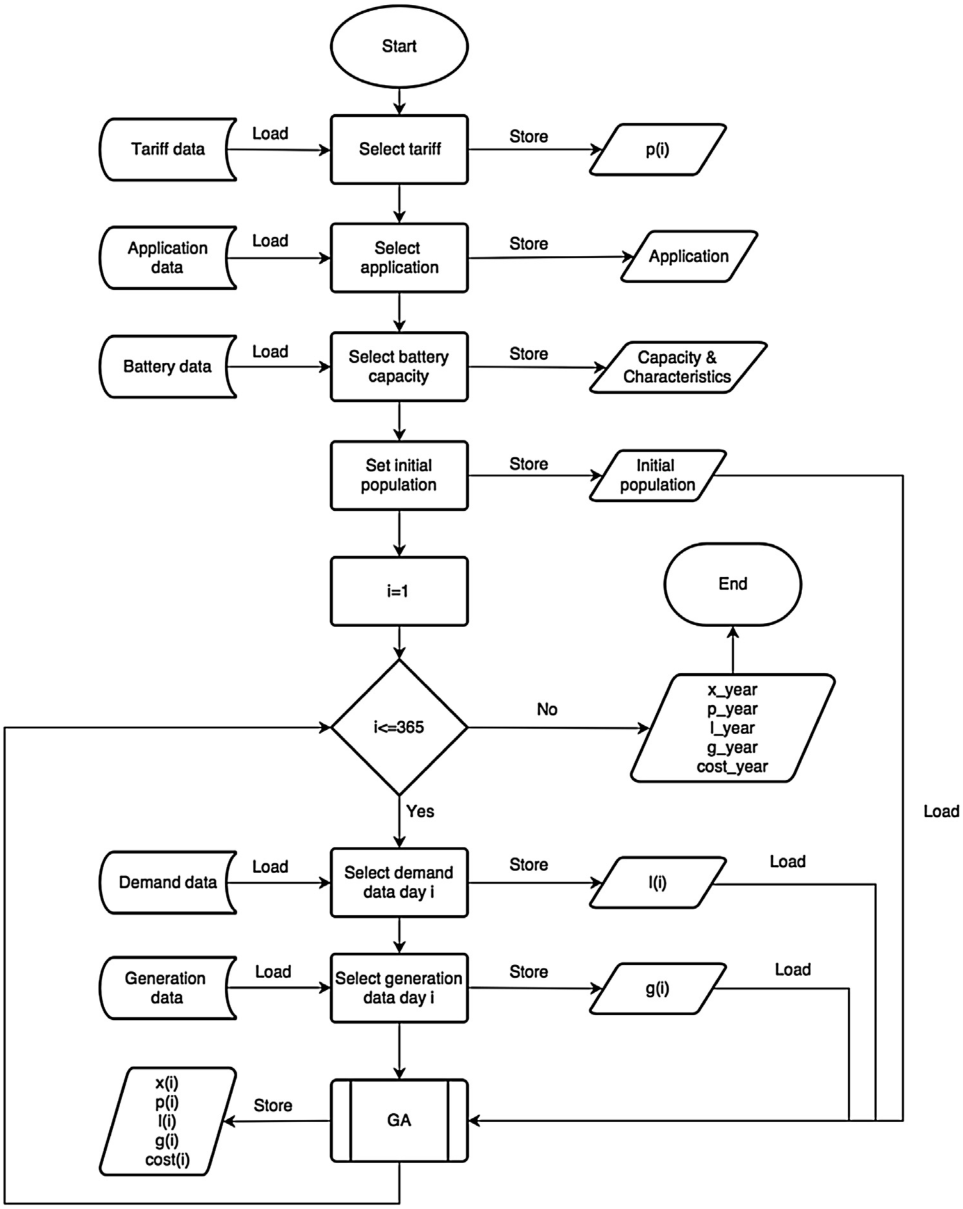

Fig. 6. Flow chart of the optimization model operation.

self-consumed PV generated electricity to the E_{PV} $(kWh/year)$total amount of PV generated electricity,

For PV systems without battery storage system, self-consumption is equivalent to the electricity generated on site that meets the load simultaneously ($E_{PV,Load}(kWh/year)$), whereas stored electricity is added to self-consumption in systems with storage [21]. Second, BS_{ES} is the battery sufficiency, expressed in Eq. (19) as the share of battery discharge E_{dis} $(kWh/year)$in the total demand E_d $(kWh/year)$, i.e. the degree to which the electricity generated on-site and subsequently stored is sufficient to meet the energy needs of the household. The origin of E_{dis} depends on the scenario and it can be PV electricity, grid electricity or a combination of both. The former indicators are calculated for a simulation period of one year. Third, the equivalent full cycles (EFC) are defined as the number of full cycles performed by the battery system throughout the battery lifetime.

$$TSC = \frac{E_{PV,Load} + E_{PV,ES}}{E_{PV}} \tag{18}$$

$$BS_{ES} = \frac{E_{dis}}{E_d} \tag{19}$$

$$EFC = \frac{E_{dis} * Lifetime}{C} \tag{20}$$

2.4.3. Techno-economic analysis

We furthermore select three indicators in order to analyze the techno-economic performance of batteries. The levelized cost of energy storage, LCOES (USD/kWh), is defined in Eq. (21). It quantifies the cost associated with the total electricity supplied by the battery throughout the life of the system (n years). The second indicator is the levelized value of energy storage, LVOES (USD/kWh). It quantifies the value associated with the battery's discharge throughout the life of the system as expressed by Eq. (22). Finally, the NPV per unit of CAPEX is calculated using Eq. (23). It indicates whether the investment in electricity storage is profitable (>0) or not (<0) depending on the battery capacity, value proposition and tariff. The NPV is calculated as the sum of the discounted cash flows over the lifetime of the battery system. The cash flows, CF_i (USD), include the avoided electricity costs due to the use of the battery system and the O&M cost (which was also assumed to be paid at the beginning of the project).

$$LCOES = \frac{CAPEX + OPEX}{\sum_{i=0}^{n} \frac{E_{dis}}{(1+r)^i}} \tag{21}$$

$$LVOES = \frac{\sum_{i=1}^{n} \frac{CF_i}{(1+r)^i}}{\sum_{i=0}^{n} \frac{E_{dis}}{(1+r)^i}} \tag{22}$$

$$NPV\ per\ Unit\ of\ CAPEX = \frac{\sum_{i=1}^{n} \frac{CF_i}{(1+r)^i} - CAPEX}{CAPEX} \tag{23}$$

3. Results

We first illustrate the electricity balance of a household which already invested in a PV system and is exploring the economic interest to add an 8 kWh Li-ion battery (which was found to be the battery capacity that minimizes the LCOES, see below Section 3.2) performing both PV self-consumption and demand-load shifting with retail tariffs DT and DynT, for a single day that represents best the totality of all profiles across the year, i.e. Monday 5 March 2012. Next, we present the annual performance indicators and the techno-economic results as a function of the battery capacity. We finally complement our results with a sensitivity analysis. Electricity balances of a representative summer and winter days are presented in supplement Section E and for other management scenarios (i.e. PV self-consumption only and demand-load shifting only), they are presented in supplement Section F. Fig. 7 shows the PV generation, demand-load, grid import, battery scheduling and SOC depending on the time-varying tariff. The daily PV generation and electricity demand for this day were 6.9 kWh and 18.7 kWh, respectively. Without the battery, the total PV power fed into the grid and total grid import would be 0.88 kWh and 12.7 kWh respectively.

The PV export is reduced by 97.4% and 95.7% with the DT and DynT. The electricity imported from the grid increased by 1.5% with the DT and diminished by 16.0% with the DynT. The fraction of

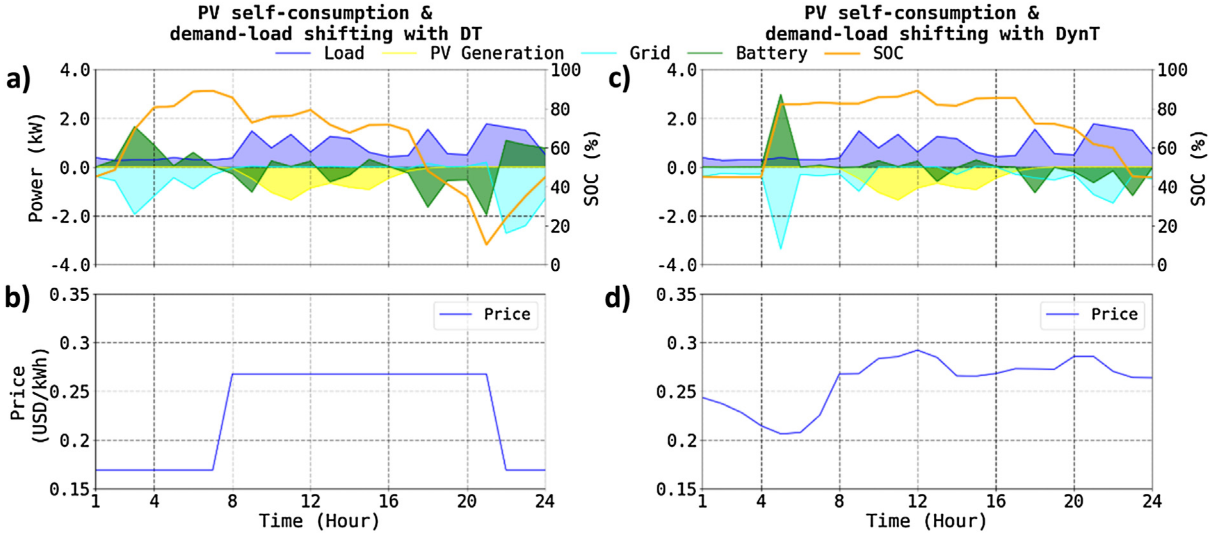

Fig. 7. Electricity balance of a Swiss household with an 8 kWh Li-ion battery performing PV self-consumption and demand-load shifting simultaneously on Monday 5 March 2012. a) PV generation, electricity demand, grid import and battery scheduling; b) Double Tariff (DT); c) PV generation, electricity demand, grid import and battery scheduling; d) Dynamic Tariff (DynT).

demand covered by the battery discharge is 34.5% and 18.8% respectively. In early hours, the algorithm exploits off-peak prices and charges the battery to about 90% with both tariffs. When PV generation starts at 8 a.m., it is supplied to the load; later, it is enough to simultaneously satisfy the load and charge the battery from 10 a.m. until 12 m. and from 3 p.m. until 4 p.m. The battery discharges when PV generation is not sufficient to cover the total demand, for example with the DT from 8 a.m. until 10 a.m., from 1 p.m. until 3 p.m. and from 5 p.m. until 10 p.m. From then onwards, the battery is charged until it achieves the initial SOC taking advantage of the off-peak prices. The schedule with the DynT differs due to the higher prices in the evening compared to the DT, thus the battery is used when PV generation is not sufficient to cover the total demand, until reach the initial SOC. As a consequence, the electricity bill reduction is greater with the DT, 34.8% versus only 8.7% with the DynT.

3.1. Performance results

Optimal performance indicators achieved by Li-ion batteries depending on the value proposition and retail tariff (compare Table 2) are presented in Table 3. The share of PV electricity directly supplied to the load (DSC) is the same for all scenarios with PV generation, and amounts to 33.8%. For batteries performing only PV self-consumption, total self-consumption (TSC) increases with rising battery capacity and results are very similar (around 65%, with less than 2% difference) regardless of the type of tariff as seen in Fig. 8. The largest capacity (i.e. 10 kWh) maximizes the total PV self-consumption as well as the battery sufficiency. The greatest number of equivalent full cycles (EFC) is obtained with small capacities in every scenario.

Table 4 presents the electricity stored annually with an 8 kWh Li-ion battery for the various scenario, depending on the value proposition and retail tariff. The type of tariff greatly affects the amount of grid charging, while charging from PV is similar in all scenarios considering PV self-consumption regardless of the tariff structure. For example, the amount of grid electricity stored almost doubles when the battery performs both PV self-consumption optimization and demand-load shifting with the DT (scenario 2) compared to operation under the DynT (scenario 5).

The type of application, PV self-consumption or demand-load shifting, is found to have a marked impact on the fraction of electricity demand met by the battery. Batteries performing demand-load shifting are able to cover larger fractions of the demand (battery sufficiency), either independently or in combination with PV self-consumption. For example, in the case of a household that did not invest in PV, but is exploring whether investing in an 8 kWh Li-ion battery performing demand-load shifting, the battery discharges 1906.1 kWh p.a. with the DT and 971.6 kWh p.a. with the DynT, i.e. 34.9% and 17.8% of the annual electricity demand respectively. For a household which already invested in a PV system and has added a battery system to combine demand-load shifting and PV self-consumption, the same battery discharges 1915.1 kWh p.a. with the DT and 1668 kWh p.a. with the DynT, i.e. covering 35.0% and 30.5% of the annual electricity demand respectively. Therefore, charging from both the grid and the PV array (scenario 2) do not increase considerably battery sufficiency (BS_{ES}) compared to only charging from the grid (scenario 3), as indicated in Table 3. The difference between the

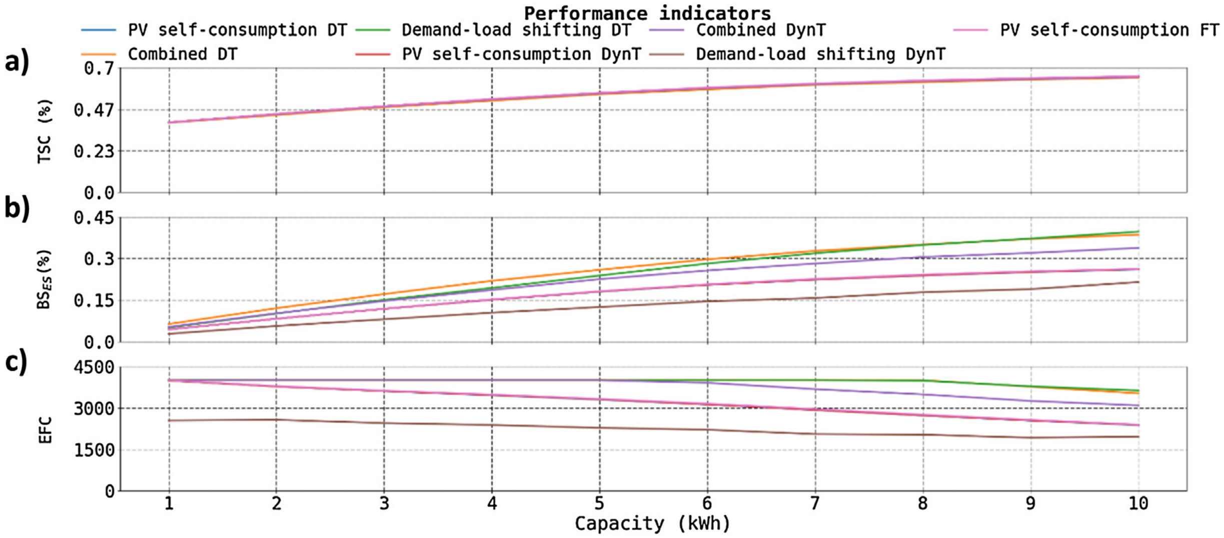

Fig. 8. Performance indicators achieved by Li-ion batteries as a function of its capacity and depending on the value proposition and tariff: a) Total self-consumption; b) Battery Sufficiency; c) EFC.

Table 3
Optimal performance and economic indicators achieved by Li-ion batteries depending on the value proposition and retail tariff. The battery capacity (kWh), for which the optimum values were achieved, is shown in brackets.

Parameter (Unit)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
TSC (%)	65% (10)	64.3% (10)	–	65.1% (10)	64.7% (10)	–	**65.2% (10)**
BS_{ES} (%)	26.1% (10)	38.6% (10)	**39.7% (10)**	26.2% (10)	33.8% (10)	21.5% (10)	26.2% (10)
EFC	3988 (1)	**4000 (1)**	4000 (1)	3986 (1)	4000 (1)	2573 (2)	3997 (1)
LCOES (USD/kWh)	0.40 (7)	**0.28 (8)**	**0.28 (8)**	0.40 (7)	0.32 (8)	0.52 (10)	0.40 (7)
LVOES (USD/kWh)	0.26 (2)	0.19 (8)	0.12 (4)	0.26 (1)	0.21 (5)	0.06 (8)	**0.29 (1)**
NPV per unit of CAPEX (USD/USD)	−0.57 (6)	−**0.50 (8)**	−0.70 (8)	−0. 56 (6)	−0.53 (7)	−0.91 (10)	−**0.49 (6)**

Table 4
Electricity stored annually in an 8 kWh battery depending on value proposition and retail tariff.

Parameter (kWh)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
PV Electricity Stored	1305.6	1294.1	–	1307.0	1322.4	–	1318.6
Grid Electricity Stored	–	621.0	1906.1	–	345.6	971.6	–
Total Electricity Stored	1305.6	1915.1	1906.1	1307.0	1668.0	971.6	1318.6

two tariffs can be explained by the DynT profile, which has higher prices compared to the DT from 10 p.m. to midnight, which is preventing battery charging during that period. The higher activity associated with grid charging impacts the EFC achieved as shown in Fig. 8.

3.2. Techno-economic results

Techno-economic results are presented in Fig. 9 as a function of the battery capacity with optimum values given in Table 3. In the case the household has already invested in a PV system and is exploring whether to invest in battery storage, similar LCOES values are achieved by batteries performing only PV self-consumption (scenarios 1, 4 and 7) with the minimal levelized cost of 0.4 USD/kWh obtained with a 7 kWh battery for all three different tariff structures. An 8 kWh battery performing PV self-consumption and demand-load shifting with the DynT (scenario 5) reaches a LCOES of 0.32 USD/kWh and 0.28 USD/kWh with the DT (scenario 2).

Charging from PV only is the best strategy to increase the value associated with battery discharging due to the larger difference between retail and PV export prices. The lower LVOES across all batteries performing PV self-consumption only is 0.23 USD/kWh (with the DT), which is greater than the LVOES obtained when both applications are performed. With the single tariff (scenario 7) the LVOES reaches the greatest values, between 0.27 and 0.29 USD/kWh, with the upper level achieved by batteries with small capacities. When PV self-consumption is combined with demand-load shifting, the LVOES is within an intermediate range of values achieved individually, i.e. 0.18 to 0.21 USD/kWh and is maximized with an 8 kWh and 5 kWh battery capacity for respectively the DT and DynT.

The best NPV per unit of CAPEX is achieved by batteries performing PV self-consumption and demand-load shifting simultaneously with the DT, in particular for batteries with large capacities, i.e. 8–10 kWh. Furthermore, batteries with smaller capacities performing only PV self-consumption with the FT (scenario 7) achieved similar NPV per unit of CAPEX. For the same type of tariff, batteries performing both applications simultaneously obtain better economic results than batteries performing only one application. Even for the systems with the most attractive NPV per unit of CAPEX values, the net cost per kWh (i.e. the difference between LCOES and LVOES) is substantial, ranging between 0.09 USD/kWh and 0.96 USD/kWh.

For a household interested in battery storage without a PV system, a battery with a capacity of 8 kWh minimizes the LCOES to 0.28 USD/kWh with the DT (scenario 3). The minimal LCOES in the case with the dynamic tariff (scenario 6) is 0.52 USD/kWh, achieved by a 10 kWh battery. Batteries performing demand-load shifting only are associated with the lowest LVOES, with the LVOES being proportional to the difference between peak and off-peak prices as suggested by Eq. (16), and ranging from 0.12 USD/kWh for a 4 kWh battery with the DT down to only 0.06 USD/kWh for an 8 kWh battery under DynT. In terms of NPV per unit of CAPEX, batteries performing demand-load shifting only are the least attractive option.

3.3. Sensitivity analysis

To verify the robustness of the model as well as the impact of our assumptions on the results, we run a sensitivity analysis which also allows to investigate the main sources of uncertainty. Sensitivity analysis for residential batteries performing PV self-consumption have already been presented in previous studies

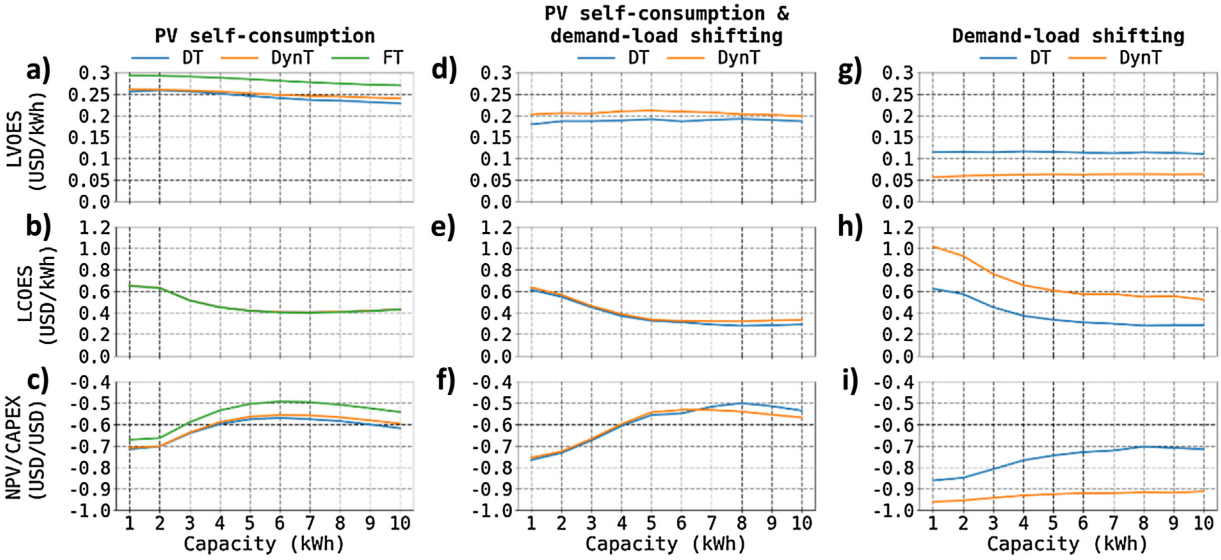

Fig. 9. Techno-economic results achieved by Li-ion batteries as a function of the capacity and depending on the value proposition and type of retail tariff. PV self-consumption optimization depending on the tariff (DT, DynT and FT): a) LCOES; b) LVOES; c) NPV per unit of CAPEX. Combined applications (DT and DynT): d) LCOES; e) LVOES; f) NPV per unit of CAPEX. Demand-load shifting application (DT and DynT): g) LCOES; h) LVOES; i) NPV per unit of CAPEX.

[16,31]. Therefore, we only address here a sensitivity analysis on the combination of applications, in particular for an 8 kWh Li-ion battery with the DT since this system achieved optimal results. The analysis includes parameters such as battery lifespan, CAPEX, rate of increase of the retail price of electricity, discount factor and the export price and evaluates their impact on the LCOES, LVOES and NPV per unit of CAPEX. For all the sensitivity cases, input data were varied within a ±30% range and in steps of 10% compared to the baseline scenario. The results are presented in Fig. 10.

The CAPEX is the parameter affecting the LCOES most strongly, followed by the lifespan, and discount rate. These results are in agreement with previous sensitivity analyses for batteries performing only PV self-consumption [16]. The lifespan is negatively correlated with the LCOES, for example, an increase of the lifespan by 30% (positive value) diminishes the LCOES by 15% while the equivalent decrease of the lifespan leads to a 37% increase of the LCOES.

The LVOES is positively correlated to the discount factor, retail prices, lifespan, with the lifespan being the most influential parameter leading to a 15% value loss when the lifespan is reduced by 30% and increased value by 13% for a 30% longer lifespan. The discount factor causes fluctuations of around 8% when it varies by 30% relative to the reference case. The retail electricity price is the second most important parameter to understand LVOES variations, with variations of one fifth for changes of ±30%. On the other hand, the export price is negatively correlated to LVOES; when it diminishes by 30% it drives the LVOES up by 7.6%. For this case of sensitivity analysis, retail prices are assumed to remain constant, while in reality, a retail price increase may also be driven by an increase in wholesale prices.

The NPV per unit of investment decreases by 23% with a 30% greater CAPEX and it increases by 43% with a 30% lower CAPEX. Lifespan is the second most influential parameter for this indicator. NPV diminishes by 31% with a 30% shorter lifespan and increases by 23% when the lifespan is 30% longer. The influence of the discount factor is less marked (9.5% increase when the discount factor decreases by 30%). When the wholesale price diminishes by 30%, it drives the NPV up by 7.7% and goes down in the same proportion in the reverse case. Finally, the break-even CAPEX for an 8 kWh battery is found to be 3055 USD (51% reduction compared with the baseline).

In order to explore break-event points compared with assumed Swiss conditions, we furthermore analyze three different criteria to achieve a positive net present value per unit of investment: 1) the required minimum battery storage system subsidy, 2) the required minimum battery cell price reduction, and 3) the required minimum rate of increase of the retail price of electricity. These parameters are analyzed individually but they could vary simultaneously. This is done for the same 8 kWh battery performing both PV self-consumption and demand-load shifting with DT. The results are presented in Fig. 11. A subsidy of 51%, a battery price reduced by 83.6%, or annual rate of increase of the retail price of electricity of 9.5% per year would lead to an economically viable case for the investment in storage capacity. According to Sauer [13], the total battery hardware cost in 2020 could reach 500 USD/kWh which represents a reduction by 31% compared with the currently observed CAPEX. With the deployment of electric vehicles which is driving Li-ion battery prices down through innovation and economies of scale, the break-even point could be achieved in the next decade. This may be supported by the increased availability of second hand batteries from the automotive sector. For example, in the context of our study the breakeven could be achieved by a battery price reduction by 50% combined with a retail price annual increase rate of 2% per year and a battery storage system subsidy of 25%.

4. Discussion

Our results show that in Switzerland, investing in batteries for households with a pre-existing PV system is not yet economically viable under realistic tariff structures, even when batteries perform demand-load shifting on top of PV self-consumption. However, this study provides useful insights by exploring under what conditions battery storage could indeed become a viable option, maybe as soon as 2020 if cost reduction projections prove to be true [13].

In terms of applications, PV self-consumption is the most economically attractive option for the end-user. The large difference between import and export prices results in greater LVOES compared to the case where demand-load shifting is added. However, combining both services leads to shorter payback time, greater value per unit of investment and greater battery sufficiency

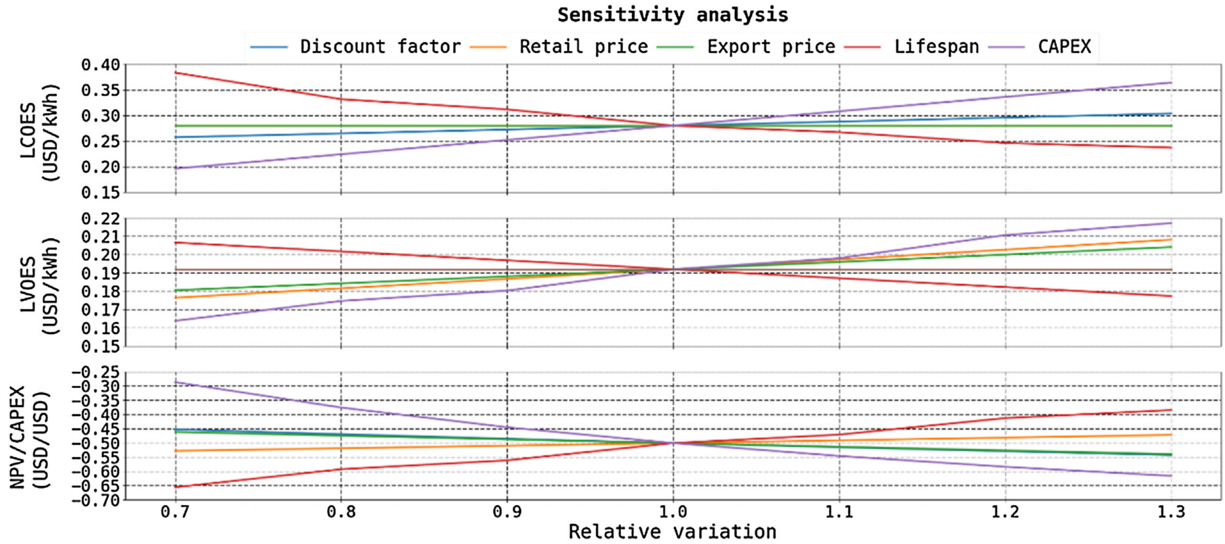

Fig. 10. a) LCOES; b) LVOES; c) NPV per unit of CAPEX for an 8 kWh Li-ion battery performing PV self-consumption optimization and demand-load shifting simultaneously under DT.

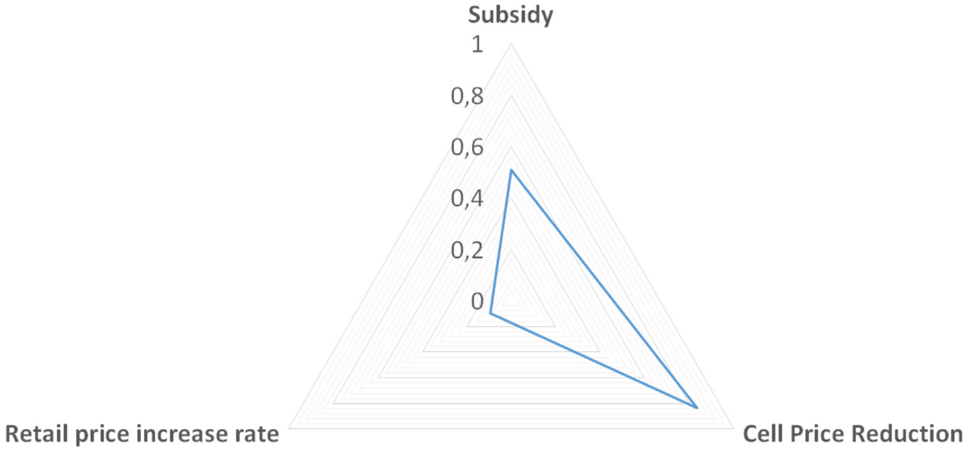

Fig. 11. Break-even points for a 8 kWh battery performing both PV self-consumption and demand-load shifting with the DT in terms of CAPEX subsidy, battery price reduction, and retail price annual increase rate.

for a given battery cost and under a given tariff structure for batteries larger than 4 kWh. Furthermore, the amount of PV self-consumption is shown to not be significantly affected when grid charging is added to PV charging. Demand load shifting only is not an attractive option and the least performing application under current conditions.

With regard to type of retail tariffs, a simple retail tariff is the best option if the battery only performs PV self-consumption, this result being in agreement with a previous study [16]. Although it is possible for battery owners to generate more value in high price periods under a dynamic tariff, we conclude that the duration of the peak period is more relevant than its magnitude. For varying price tariffs (DT and DynT), it is economically attractive to add demand-load shifting to the value proposition for batteries larger than 4 kWh, since this allows the battery to benefit from the price difference at times when PV does not generate much electricity (e.g., winter) but also profit from high value discharges at peak time driven by PV generation. The type of retail tariff has an important impact on the techno-economic results. The main difference between the DT and the DynT used in this work is the absence of price valleys in the evenings for the DynT, preventing the battery to be charged in the evenings, resulting in a lower number of battery cycles. This makes the proposed DynT be less attractive than the DT for battery storage.

Regardless of the battery capacity, combining both applications increases the battery annual discharge helping to reduce the LCOES (albeit only very slightly at low battery capacities). Likewise, the best NPV per unit of CAPEX was achieved by batteries performing both applications simultaneously with a DT for the greater capacities (i.e. 8–10 kWh), while for smaller capacities batteries performing only PV self-consumption with FT offer the best results. We also find that for batteries performing PV self-consumption, the battery use (i.e. battery sufficiency) is independent of the type of tariff.

Our results are in line with those presented in the literature [10,11,17,18]. Table 5 shows a comparison of the results presented in this work and the results from other studies analyzing similar cases. In particular, Luthander et al. found the PV self-consumption increase using a battery with a capacity of 0.5-1 kWh per installed kW of PV power to be between 13 and 24% [8]. Using battery capacities in the same range, we found a self-consumption increase in the range of 14.5-31%. Parra and Patel found optimum LVOES for the largest battery capacities (i.e. 20 kWh) [16] while we found only a slight dependence on the capacity with somewhat higher LVOES values for the smallest battery capacities (i.e. 1 kWh). The differences may be caused by the round trip efficiency which was modelled by Parra and Patel [16] as a function of the battery capacity as well as the increased lifetime of larger capacities due to a less intensive use. Nevertheless, our results are in agreement in terms of optimal battery capacities for NPV. The difference on the optimum battery-sufficiency (BS_{ES}) values may be related to the optimization time, while Parra and Patel [16] let the algorithm optimize for a year, we focused on daily optimization for all 365 days of the year, as well as in the deterministic nature of their algorithm.

Although our study presents a robust optimization method for different types of applications, tariffs and battery capacities, we acknowledge some limitations. The model assumes perfect

Table 5
Comparison between the results from this work and results from previous similar studies addressing these applications.

Study	Value proposition	Criteria	Performance	
			This work	Other
Luthander et al. [8]	PV Self-consumption & Combined	SC (%)	14.5-31	13-24
Parra and Patel [16]	PV Self-consumption	LCOES (USD/kWh) LVOES (USD/kWh) BS (%)	0.40 0.26-0.3 26	0.46 0.3-0.36[a] 17,29,43[b]
Davis and Hiralal [17]	Demand-load shifting	NPV per unit of CAPEX (USD/USD)	-0.72	-0.75
Yoon and Kim [9]	Combined	Daily bill reduction with DT (USD) Daily bill reduction with DynT(USD)	9.5 8.3	10.9 10.6

[a] Achieved for a 20 kWh battery.
[b] DynT, DT & FT for a 20 kWh battery.

forecast while day-ahead scheduling algorithms are also subject to some uncertainty in terms of PV generation and electricity demand under real conditions [20]. Furthermore, we calculate the various life-cycle indicators, e.g., equivalent full cycles and levelized cost based on a one-year operation, i.e. without considering battery performance reduction due to ageing. Future work will include considerations about weather and load forecast uncertainty along with battery ageing. Additionally, results were obtained for a single dwelling and future research will evaluate the impact of different electricity consumption profiles, PV systems and yet different tariff structures. Additionally, residential batteries can perform other applications such as system wide demand peak shaving and frequency control in addition to PV self-consumption and demand-load shifting. Future research will explore such applications as a way of increasing the economic attractiveness of residential batteries. Finally, household access to innovative financing options [2] and lower interest rates for capital may incentivize the installation of residential battery systems.

5. Conclusions

In this study we have investigated if and under what conditions batteries performing both PV self-consumption and demand-load shifting simultaneously, i.e. complementing battery charging by PV-sourced electricity with grid electricity, helps to create an economic case for residential batteries larger than 4 kWh. A GA was used to optimize the battery scheduling covering seven scenarios including three different retail tariffs under the hypothesis of day-ahead weather and load-demand perfect forecast. We assumed a Li-ion techno-economic model as well as actual PV and demand data monitored in a house located in Switzerland.

Our results show that, for a household which already invested in a PV system, adding battery storage is not yet economically viable in Switzerland regardless of the tariff structure and battery capacity. If the investment is made for non-economic reasons, for a given tariff, the addition of demand-load shifting to PV energy time-shift barely improves the economic performance of battery systems while it leads to similar self-consumption levels as for scenarios that only optimize PV self-consumption. However, the benefits for the electricity system (e.g. reduction of electricity use at on-peak time), which are not included in the present study, should be analyzed. A large battery capacity under DT is the preferred case. If the household has a single flat tariff, a small battery capacity for only PV self-consumption is preferable.

According to our results and in terms of economic attractiveness, consumers with dynamic tariff structures should perform both PV self-consumption and demand-load shifting simultaneously; or alternatively change to a flat rate tariff and perform only PV self-consumption. Other considerations such as heat pumps for heating may call for retaining the variable tariff. The type of value proposition and retail tariff also affect the optimal battery capacity. In particular, we find that optimal solutions for combined services require slightly larger battery capacities. For dynamic tariff structures, we conclude from the comparison of the double tariff with the dynamic tariff that the duration of the peak period has a stronger influence on the results than its magnitude.

For a household without a PV system, investing in storage capacity for demand-load shifting does not make economic sense under the considered conditions (for households in Switzerland), whatever the battery capacity and tariff structure. If this strategy is nevertheless pursued, large capacity batteries have a better performance regardless of the tariff structure and the batteries perform better under the presented DT structure.

Despite not being economically attractive currently, residential batteries are one of the key markets for stationary energy storage together with ancillary services in the short term. This study identifies optimal management solutions to address the gap between cost and value of home storage solutions. Furthermore, anticipated cost cuts in battery technology, the consideration of value propositions with combined services beyond PV self-consumption and demand-load shifting and facilitated access to financing options (e.g., Germany) can support market penetration of PV-coupled batteries.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at 10.1016/j.est.2017.06.002.

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