



# Economic benefits of combining self-consumption enhancement with frequency restoration reserves provision by photovoltaic-battery systems

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## HIGHLIGHTS

- Development and comparison of six battery storage dispatch strategies.
- Strategies applied on 48 residential and 42 commercial PV battery systems.
- Limited reduction of self-consumption combined with large increase in profitability.
- Provision of frequency restoration reserves is recommended for profitable investments.

## ARTICLE INFO

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## ABSTRACT

Residential and commercial photovoltaic (PV) battery systems are increasingly being deployed for local storage of excess produced PV energy. However, battery systems aimed at increasing self-consumption are not constantly put to use. Additional battery storage capacity is available for a second application to improve the profitability of an energy storage system. One of these options is the provision of frequency restoration reserves (FRR) to the electricity balancing market. This provision can be either negative to compensate for excess power supply, or positive to compensate for excess demand on the power market. This study assesses the benefits for residential and commercial PV-battery systems by combining PV energy storage for higher self-consumption with provision of FRR. Six battery storage dispatch strategies were developed and assessed on the technical and economic performance of 48 residential and 42 commercial PV-battery systems. These systems were modelled over their economic lifetime with a time resolution of 5 min and with historical energy consumption measurements and market prices. FRR provision results in a small drop in the self-consumption rate of 0.5%. However annual revenues are significantly increased. Using battery storage systems only for self-consumption is not profitable with the assumptions used in this study. Provision of negative FRR substantially reduces the electricity bought with the consumption tariff and increases investment attractiveness substantially. Prioritizing the provision of FRR over self-consumption enhancement results in even higher revenues, but significantly reduces self-consumption. We recommend FRR provision to economically investment in residential battery storage systems. Commercial systems need prioritization of both positive and negative FRR provision over self-consumption for a cost-effective investment. In conclusion, combining enhancement of PV self-consumption with the provision of frequency restoration reserves leads to profitable investments.

## 1. Introduction

Photovoltaic (PV) battery systems are increasingly deployed in urban areas to store excess PV energy for later use. In this way, the effect of intermittence of PV generated electricity on a low voltage network is reduced and self-consumption is increased [1]. Furthermore, CO<sub>2</sub> emissions from fossil-based backup power generation are reduced, particularly when curtailment of renewable energy generation is avoided [2].

The cost of stationary battery energy storage systems (BESS) is rapidly decreasing and this is expected to continue due to their current and future potential of deployment [3]. However, the benefits of storing PV produced electricity are limited, especially in areas with small differences between prices of consumption and feed-in tariffs [4]. The added value that can be generated for each kWh of stored PV energy is restricted. Also, battery systems only use part of their potential storage capacity, especially in locations with large seasonal difference in PV electricity generation. Stationary batteries can be used for a broad

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**Nomenclature****Abbreviations**

AC	alternating current
BESS	battery energy storage systems
BOS	balance of system
CEC	California Energy Commission
DC	direct current
DOD	depth of discharge
EPC	engineering procurement construction
FCE	full cycle equivalents
FCR	frequency containment reserves
FRR	frequency restoration reserves
PV	photovoltaics
SOC	state of charge
TSO	transmission system operator

**Battery storage dispatch strategies**

FRRO	FRR provision only
PFRR	prioritize FRR provision over self-consumption
PFRRN	prioritize providing only negative FRR over self-consumption
PSC	prioritize self-consumption over FRR provision
PSCN	prioritize self-consumption over providing negative FRR only
SCO	self-consumption only

**Performance indicators**

$CF_{ET}$	cash flow under the electricity tariffs [€]
$CF_{FRR}$	cash flow from frequency restoration reserves provision [€]
$D_{BESS}$	battery storage capacity degradation [%]
$R_{BESS}$	battery energy storage system revenues [€]
FRRSR	frequency restoration reserve storage ratio [%]
PBP	payback period [years]
PI	profitability index
SCCR	self-consumption contribution rate [%]
SUR	storage use rate [%]

**Parameters**

$\Delta t$	timestep of 5 min
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$\Delta E_{B \text{ pot}}$	battery charge or discharge energy potential [Wh]
$\Delta E_B$	battery charge or discharge energy [Wh]
	difference in bought electricity [Wh]
$\Delta E_{\text{sell}}$	difference in sold electricity [Wh]
$\eta_{\text{charge}}$	battery charge efficiency [%]
$\eta_{\text{discharge}}$	battery discharge efficiency [%]
$\pi_{\text{cons}}$	consumption tariff [€/Wh]
$\pi_{\text{feed-in}}$	feed-in tariff [€/Wh]
$\pi_{\text{neg}}$	price for negative FRR provision [€/Wh]
$\pi_{\text{pos}}$	price for positive FRR provision [€/Wh]
$C_{B \text{ BOS}}$	battery balance of system cost [€]
$C_{B \text{ EPC}}$	battery engineering procurement construction cost [€]
$C_{B \text{ store}}$	battery storage system cost [€]
$CCF$	cumulative cash flow [€]
$D_{\text{cal}}$	battery calendric degradation [%]
$D_{\text{cyc}}$	battery cycle degradation [%]
$E_{B, t}$	battery state of charge [Wh]
$E_{B \text{ max}}$	maximum battery state of charge [Wh]
$E_{B \text{ min}}$	minimum battery state of charge [Wh]
$E_{\text{buy PV-B}}$	electricity bought with a PV-battery system [Wh]
$E_{\text{buy PV}}$	electricity bought with a PV system [Wh]
$E_{\text{sell PV-B}}$	electricity sold with a PV-battery system [Wh]
$E_{\text{sell PV}}$	electricity sold with a PV system [Wh]
$f_{B \text{ OM}}$	battery operation and maintenance cost factor [%]
$I_{BESS}$	battery investment cost [€]
$L_{\text{cal}}$	calendric lifetime [years]
$L_{\text{econ}}$	economic lifetime [years]
$N_{FCE}$	number of full cycle equivalents [#]
$P_{B \text{ charge}}$	power charged to the battery [W]
$P_{B \text{ discharge}}$	power discharged to the battery [W]
$P_{B \text{ from PV}}$	PV power used to charge the BESS [W]
$P_{B \text{ inv max}}$	battery inverter rating [W]
$P_{B \text{ inv}}$	battery inverter load [W]
$P_{B \text{ pot}}$	battery load potential [W]
$P_D$	electricity demand [W]
$P_{\text{neg}}$	power provided for negative FRR [W]
$P_{\text{pos}}$	power provided for positive FRR [W]
$P_{\text{PV}}$	PV power [W]
$r$	discount rate [%]
$S_{B \text{ inv}}$	battery inverter size [W]
$S_{B \text{ store}}$	battery storage capacity [Wh]
$t$	timestep
$y$	year

range of use cases and are therefore seen as a multi-purpose technology [5]. Combining multiple applications improves the financial attractiveness of these storage systems [6].

A potential additional application of PV-battery systems is offering power and energy to the balancing and ancillary services markets. Two balancing services can be distinguished that are traded on the imbalance markets for the Netherlands, namely frequency containment reserves (FCR) and frequency restoration reserves (FRR). FCR (also known as primary control reserves), are the first tier to balance the grid and are automatically activated. The balancing power capacity is contracted in blocks of one week and the reserved capacity is remunerated [7]. Moreover, the BESS has to be able to deliver the contracted FCR, otherwise the balancing service provider receives financial penalties.

FRR (also known as secondary control reserves) are provided to restore the FCR and to compensate for excess of power supply or an excess of demand. Provision of FRR can be either mandatory or voluntary. Mandatory contributors place bids of energy provision (positive) or energy subtraction (negative) capacities on a bid ladder. These

are delivered in blocks of 15 min and can be proposed to the market up to one hour before dispatch. The bid ladder determines the minutely imbalance FRR price. Voluntary contributors observe the current imbalance price and determine if they want to deliver FRR. In case of mandatory contribution, all positive and negative energy delivered is remunerated within a block of 15 min. In case of voluntary contribution, only the energy provision is remunerated if all energy within a 15 min block is positive provision, or all is negative provision [8]. FCR and FRR are contracted and remunerated by the Dutch transmission system operator (TSO) TenneT, in the Netherlands.

**1.1. Literature review**

Few studies were found that assess the combination of self-consumption enhancement with provision of control reserves. The ones found can be distinguished between studies that combine self-consumption with FCR, or with FRR. Revenues of storage systems that combine self-consumption with provision of FCR are about three times

higher than if the BESS was solely used for self-consumption enhancement [9]. One study from Germany showed that annual revenue of €185/kW can be obtained from FCR provision by a residential PV-battery system. However, the self-sufficiency was reduced with 18.9% [10]. In addition, larger economic profitability was found for FCR provision than for self-consumption increase for a vanadium flow battery [11]. A significant increase in profitability of battery storage was observed when PV-self-consumption was combined with negative FRR provision to the German market [12]. Also, large scale community storage was found economically feasible for FRR provision [13].

Aggregators can operate these residential and commercial battery systems on this market. Lately, there have been a few commercial parties that are interested in combining self-consumption with FCR provision [14,15]. The request for provision of grid balancing is expected to increase with a large share of renewable generators in the electricity grid [16]. Consequently, grid balancing costs are expected to increase and are a potential barrier for future growth of variable renewable resources [17]. PV-battery storage systems might be useful to provide solutions to overcome this barrier.

## 1.2. Research aim

Literature shows a high potential value that can be added by BESS with providing FCR and FRR. Despite this high potential only a few studies were found concerning this prospective. Besides, these studies use a single demand profile and one year of data. Furthermore, the influence on PV self-consumption, battery degradation or investment attractiveness is not researched in detail. The lack of these results restrains the development of PV-battery systems for balancing services.

In this study, we aim to assess the technical and economic performance of combining self-consumption enhancement with frequency restoration reserves provision. We select FRR since its market conditions are more flexible than the FCR market. Furthermore, a mandatory contribution to the FRR market was selected to obtain both revenues for positive and negative provided FRR. We use historical FRR prices from 2011 to 2016 of the Dutch market and measured energy demand of 48 residential and 42 commercial buildings. We assessed all systems using six battery storage dispatch strategies, each with a different aim. In addition, we conducted a sensitivity study to identify the most important parameters on economic profitability of a PV-battery system.

The combination of a large range of systems with six different battery dispatch scenarios shows a wide variety of technical and economic results. These novel results provide a first insight in the added value that PV-battery system have when tapping into the frequency restoration reserve market. We identify new directions for future research and help commercial parties to contribute in this field. This will encourage the deployment of multiple purposes battery systems. Subsequently, this will enable a higher share of fluctuating renewable energy sources into the energy systems and help the transition towards a more sustainable energy system.

The remainder of this study is arranged as follows. Section 2 explains the battery storage dispatch strategies, the used data and the technical and economic performance indicators. Section 3 presents the results on the technical assessment of the battery storage dispatch strategies, followed by the economic assessment in Section 4. Section 5 examines the sensitivity of the reference parameters. Section 6 discusses the market assumptions and the implementation considerations of the dispatch strategies. Section 7 finalises with the key conclusions.

## 2. Methods

The methodology is explained in the following four subsections. Section 2.1 describes the battery storage dispatch strategies and the used model equations. Section 2.2 explains the technical and economic assumptions of the reference PV-battery systems. The used input time series are explained in Section 2.3. Lastly, Section 2.4 describes the

technical and economic performance indicators, used to assess the dispatch strategies.

### 2.1. Battery storage dispatch strategies

Six battery storage dispatch strategies were developed to assess the impact on self-consumption, FRR provision and combinations of self-consumption enhancement with FRR provision. Provision of FRR can either be positive or negative: positive FRR delivers electricity to the grid and negative FRR withdraws electricity from the electricity grid. The developed strategies are:

1. PV self-consumption enhancement only (SCO).
2. Provision of frequency restoration reserves only (FRRO).
3. Prioritizing PV self-consumption over providing FRR (PSC).
4. Prioritizing PV self-consumption over providing only negative FRR (PSCN).
5. Prioritizing FRR provision over PV self-consumption (PFRR).
6. Prioritizing only negative FRR provision over PV self-consumption (PFRRN).

The SCO and FRRO strategies consist of a single application and are examined to distinguish the individual impacts of these applications. The PFRR and PFRRN strategies assess the enhancement of self-consumption as a primary application and provision of FRR as a secondary application. The PFRR and PFRRN strategy assessed the provision of FRR as primary storage application and self-consumption as secondary application.

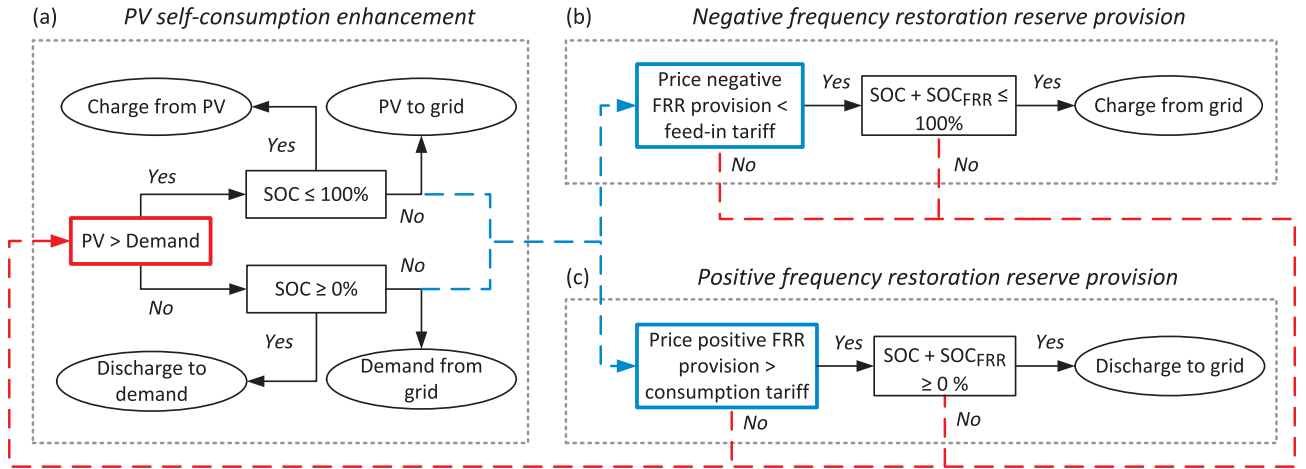
The storage dispatch strategies were assessed using a PV-battery model developed in Python (v3.5). The model simulated the battery charging and discharging behaviour with a timestep ( $\Delta t$ ) of 5 min. A schematic representation of the model is shown in Fig. 1. This model consists of three separate blocks: enhancement of PV self-consumption (a), provision of negative FRR (b) and provision of positive FRR (c). The SCO strategy only uses block (a) and the FRRO block (b) and (c). The PSCN and PFRRN use block (a) and (b). The PSC and PFRR strategies use all three blocks.

#### 2.1.1. PV self-consumption enhancement

The SCO strategy operates according to the PV self-consumption enhancement block only (Fig. 1(a)). The difference between PV power production ( $P_{PV}$ ) and electricity consumption ( $P_D$ ) is assessed for each time-step (see red<sup>1</sup> rectangle). The battery is charged when excess PV and battery capacity is available. The battery capacity is assessed using the battery state of charge (SOC). Discharging happens if demand exceeds PV production and energy capacity is available in the battery. If no battery capacity is available to charge or discharge, then excess PV electricity is fed into the grid or requested electricity demand is imported from the grid.

A rule based algorithm was used to define the battery inverter power ( $P_{B\text{ inv}}$ ) and the battery state of charge ( $E_{B,t}$ ) for each time moment. First the potential power ( $P_{B\text{ pot}}$ ) for charging or discharging the battery was determined. This power is limited by the battery inverter rating ( $P_{B\text{ inv max}}$ ). Then, the potential energy ( $\Delta E_{B\text{ pot}}$ ) was calculated which could be charged to, or discharged from, the battery. This depends on the charge efficiency ( $\eta_{\text{charge}}$ ) or discharge efficiency ( $\eta_{\text{discharge}}$ ) of the battery storage system. Next, the actual charged or discharged energy ( $E_{B\text{ pot}}$ ) was determined. These are related to the current battery SOC the minimum SOC ( $E_{B\text{ min}}$ ) and maximum SOC ( $E_{B\text{ max}}$ ). This set of equations are specific for the PV self-consumption enhancement (see block (a)) and are given in Eq. (1).

<sup>1</sup> For interpretation of color in Fig. 1, the reader is referred to the web version of this article.



**Fig. 1.** Schematic overview of the model steps used in the battery storage dispatch strategies. The model contains of three blocks: PV self-consumption enhancement (a), negative frequency restoration reserve provision (b) and positive frequency restoration reserve provision (c).

$$P_{B \text{ pot}} = \begin{cases} P_{PV} - P_D & \text{if } |P_{PV} - P_D| < P_{B \text{ inv max}} \\ P_{B \text{ inv max}} & \text{if } |P_{PV} - P_D| \geq P_{B \text{ inv max}} \end{cases} \quad (1a)$$

$$\Delta E_{B \text{ pot}} = \begin{cases} P_{B \text{ pot}} \cdot \eta_{\text{charge}} \cdot \Delta t & \text{if } P_{B \text{ pot}} > 0 \\ \frac{P_{B \text{ pot}}}{\eta_{\text{discharge}}} \cdot \Delta t & \text{if } P_{B \text{ pot}} \leq 0 \end{cases} \quad (1b)$$

$$\Delta E_B = \begin{cases} \Delta E_{B \text{ pot}} & \text{if } E_{B,t} + \Delta E_{B \text{ pot}} \geq E_{B \text{ min}} \\ \Delta E_{B \text{ pot}} & \text{if } E_{B,t} + \Delta E_{B \text{ pot}} \leq E_{B \text{ max}} \\ E_{B,t} - E_{B \text{ min}} & \text{if } E_{B,t} + \Delta E_{B \text{ pot}} < E_{B \text{ min}} \\ E_{B \text{ max}} - E_{B,t} & \text{if } E_{B,t} + \Delta E_{B \text{ pot}} > E_{B \text{ max}} \end{cases} \quad (1c)$$

Lastly, the battery inverter power and battery state of charge for the next time step were determined according Eq. (2).

$$E_{B,t+1} = E_{B,t} + \Delta E_B \quad (2a)$$

$$P_{B \text{ inv}} = \begin{cases} \left( \frac{\Delta E_B}{\Delta t} \right) & \text{if } \frac{\Delta E_B}{\Delta t} > 0 \\ \eta_{\text{charge}} & \text{if } \frac{\Delta E_B}{\Delta t} > 0 \\ \frac{\Delta E_B}{\Delta t} \cdot \eta_{\text{discharge}} & \text{if } \frac{\Delta E_B}{\Delta t} \leq 0 \end{cases} \quad (2b)$$

### 2.1.2. Negative and positive FRR provision

The FRRO strategy uses the negative and positive FRR provision assessment blocks (Fig. 1(a) & (b)). Negative FRR provision is feasible if the price of negative provision ( $\pi_{\text{neg}}$ ) is smaller than the feed-in tariff

( $\pi_{\text{feed-in}}$ ). If negative FRR are provided than the price of negative provision is paid to the TSO. Positive FRR provision is feasible if the price of positive provision ( $\pi_{\text{pos}}$ ) is higher than the consumption tariff ( $\pi_{\text{cons}}$ ). In this case the price for positive provision is paid by the TSO. We used the consumption and feed-in tariff as the price points for feasible delivery of positive and negative FRR. Therefore it was possible to make a comparison with the other five dispatch strategies. Besides, the state of charge (SOC) of the battery storage must be sufficient to provide FRR. We assume that if power is provided to the FRR market, then it is similar to the maximum inverter rating. As a result, the pooling of battery storage systems from multiple residential or commercial systems will be less complex for an aggregator.

The battery state of charge in the negative and positive frequency restoration reserves provisions blocks were calculated using the following approach. First, the potential battery state of charge was determined by assessing the feasibility of FRR provision. Then, the actual energy that could be charged or discharged was determined, see Eq. (3). Lastly, battery inverter power and battery SOC were calculated according to Eq. (2).

$$\Delta E_{B \text{ pot}} = \begin{cases} \frac{P_{B \text{ inv max}}}{-1} \cdot \eta_{\text{charge}} \cdot \Delta t & \text{if } \pi_{\text{neg},t} < \pi_{\text{feed-in}} \\ 0 & \text{if } \pi_{\text{neg},t} \geq \pi_{\text{feed-in}} \\ \frac{P_{B \text{ inv max}}}{\eta_{\text{discharge}}} \cdot \Delta t & \text{if } \pi_{\text{neg},t} > \pi_{\text{cons}} \\ 0 & \text{if } \pi_{\text{pos},t} \leq \pi_{\text{cons}} \end{cases} \quad (3a)$$

**Table 1**

Reference residential and commercial PV-battery system parameters used to model the dispatch scenarios.

Category	Parameter	Residential	Commercial	Unit	Sources
Technical	PV system size	1		kW <sub>PV</sub> MWh <sub>demand</sub> <sup>-1</sup>	Own assumption
	PV system degradation	0.5		%/year	[18]
	Storage capacity	1		kWh <sub>BESS</sub> MWh <sub>demand</sub> <sup>-1</sup>	[19,20]
	Battery inverter rating	0.5		kW/kWh <sub>BESS</sub> MWh <sub>demand</sub> <sup>-1</sup>	[21]
	Total number of FCE	5000		#	[22]
	Calendric lifetime	15		years	[22]
	Round trip DC $\eta$ loss	7.8		%	[21]
Economic	Storage pack cost	200		€/kWh <sub>BESS</sub>	[23]
	BOS battery system	150	100	€/kW	[24]
	EPC battery system	150	100	€/kW	[24]
	O&M battery system	1		%/year	[25]
	Economic lifetime	25	20	years	Own assumption
	Discount rate	2	4	%/year	[26]
	Consumption tariff	0.178	0.106	€/kWh	[27]
	Feed-in tariff	0.11	0.04	€/kWh	[28,29]



$$\Delta E_B = \begin{cases} \Delta E_{B \text{ pot}} & \text{if } E_{B,t} + \Delta E_{B \text{ pot}} \geq E_{B \text{ min}} \\ \Delta E_{B \text{ pot}} & \text{if } E_{B,t} + \Delta E_{B \text{ pot}} \leq E_{B \text{ max}} \\ 0 & \text{if } E_{B \text{ max}} < E_{B,t} + \Delta E_{B \text{ pot}} < E_{B \text{ min}} \end{cases} \quad (3b)$$

### 2.1.3. Combining PV enhancement and FRR provision

The PSC strategy combines the PV self-consumption enhancement block with the provision of negative and positive FRR. This strategy starts with similar steps as in the SCO strategy, specifically the assessment of the difference between PV and electricity consumption. If the calculated battery inverter output was zero, then the strategy continued to assess the feasibility of negative FRR provision (see dashed blue lines in Fig. 1). This is feasible if the price of negative provision is smaller than the feed-in tariff. Consequently, all negative provided FRR is bought for a lower price than sold excess PV energy and therefore self-consumption is always profitable. Positive FRR provision is feasible when the price of positive provision is higher than the consumption tariff and battery capacity is available. Hence, electricity is always sold with a higher price than it is bought. The PSCN strategy is almost similar as the PSC strategy, yet only provision of negative FRR is possible. Therefore all energy that is charged in the battery is considered as self-consumed energy.

The PFR strategy starts with the assessment of providing negative and positive FRR. If the battery inverter output is zero, then the dispatch strategy continues to the PV self-consumption block (see dashed red lines in Fig. 1). The PFRN strategy only assesses the provision of negative FRR thus all excess energy stored from a PV system is accounted for as self-consumption. If the battery inverter was not used for self-consumption enhancement, or provision of FRR, then the algorithm continues with the next time step.

## 2.2. Reference PV-battery system

A reference PV-battery system was developed to assess the dispatch strategies for residential and commercial battery storage systems. A similar set of technical parameters were selected for residential and commercial systems, enabling comparison of the demand patterns. An overview of the technical and economic reference parameters used for residential and commercial systems is given in Table 1. Some economic parameters were set differently for residential and commercial systems due to the different system capacities and policies in place.

### 2.2.1. Technical parameters

The layout of an alternating current (AC) coupled lithium-based PV-battery system was selected. This consists of a PV array that is connected to the electricity grid by a PV inverter and a battery storage system that is connected with a battery inverter to the grid. AC coupled systems are most widely used in the literature and are very suitable for retrofit existing PV systems with electricity storage [19].

The modelled annual average PV electricity production (between 2012 until 2016) is 984 kWh for each kWp of installed PV capacity. Typically in the Netherlands, the PV installed capacity is chosen such that is able to cover the annual electricity consumption. Therefore, the installed PV system size was set to 1 kWp for each MWh of annual electricity consumption. A linear annual degradation of the PV yield reduction of 0.5%/year was assumed [18].

The battery energy storage capacity was set to 1 kWh for each MWh of annual electricity consumption, based on previous studies [19,20]. The battery inverter rating was set to 0.5 kW. This charge rate is commonly used, for example with a Tesla Powerwall [21]. Battery degradation was modelled for a calendric lifetime of 15 years and 5000 full cycle equivalents [22]. A battery round trip direct current (DC) efficiency loss of 7.8% was assumed, almost identical to a commercially available Tesla Powerwall. Normally, a battery system is operated in a limited SOC range in order to limit aging and for safety reasons.

However, in this research we want to assess the impact of utilizing the full battery capacity. For this reason, the minimum SOC was set to 0% and the maximum SOC to 100% of the battery storage capacity.

The battery inverter efficiencies were retrieved from the parameters of the inverter efficiency curve of a SMA Sunny Boy Storage inverter, with a step size of 0.01% [30]. The used inverter curve resulted in a California Energy Commission (CEC) efficiency of 96.4%. A battery inverter standby consumption of 0.1% from the rated inverter power was assumed. We assumed a similar maximum AC input as AC output for the battery inverter. Battery state of charge limits were set to a minimum of 0% and a maximum of 100%, thus the full battery storage capacity was available for electricity storage.

### 2.2.2. Economic parameters

We assumed a relative low battery storage pack cost of 200 €/kWh for residential and commercial systems [23]. Balance of system (BOS) and Engineering procurement construction (EPC) cost were both set to 150 €/kW for residential systems [24]. Larger system sizes are required for commercial systems, thus we assumed lower BOS and EPC cost for commercial systems of 100 €/kW.

Operation and maintenance costs of the battery storage systems were assumed to be 1% for both residential and commercial systems [25]. We assumed that the battery system is integrated in the energy system of the building. Consequently, a relative long economic lifetime was assumed of 25 years for residential systems and 20 years for commercial systems. Current guarantees for PV modules and micro inverters are in similar ranges. Replacements of broken components before the end of lifetime are included in the operation and maintenance cost. The battery pack will not be replaced after the economic lifetime. Discount rates of 2% for residential and 4% for commercial systems were selected, based on the current low rates for the Netherlands [26]. A higher discount rate for commercial systems was selected due to a shorter lifetime and a lower risk acceptance of commercial parties.

The consumption tariff for residential systems was set to 0.178 €/kWh, based on the average tariff prices for 2014, 2015 and 2016. Commercial systems have a lower consumption tariff of 0.106 €/kWh, mainly due to lower electricity tax for larger energy consumers [27]. Residential systems in the Netherlands profit from a net metering policy for power sold back to the grid, although this policy is currently under debate. Hence, we assumed a feed-in tariff for residential systems 0.11 €/kWh, based on the present feed-in subsidy for stimulation of sustainable energy production [28]. For commercial systems we assumed 0.04 €/kWh based on the average wholesale electricity prices (day-ahead market) in the Netherlands from 2014 until 2016 [29].

### 2.3. Input time series

The storage dispatch strategies were modelled for an economic lifetime of 20 or 25 years in the reference scenario. PV yield, demand and FRR prices from 2012 until 2016 were used as input patterns. We repeated the patterns of these five years to create an input pattern of 20 years. Thus, data of the year 2012 were used in the first, sixth, eleventh and sixteenth year.

PV yield patterns were modelled with the python package PVLIB (v0.5.0) [31]. This open source package contains PV system performance models and validated atmospheric functions. Radiation, temperature, dew point temperature, wind speed and pressure were measured on a weather station in De Bilt, the Netherlands. Measurement intervals of radiation (10 min) and remaining weather parameters (one hour) were linearly interpolated to 5 min. These atmospheric parameters were combined with module parameters of the Sanyo HIP-225HDE1 to model a DC PV yield pattern. The DC power pattern was converted to AC power pattern using efficiency parameters from the Enphase Energy M210 inverter which has 95.5% CEC efficiency. Due to a relative low temperature coefficient temperature of the Sanyo module, the influence of temperature in the model is limited. The PV

system was modelled using a PV orientation of 180° module surface azimuth and 35° module tilt. The PV inverter power rating was set to 1 kW/kWp. The PV system yield pattern was linearly scaled to reach a performance ratio of 85%, corresponding with high performing systems for the Netherlands [32]. The annual modelled PV yield ranges between 935 kWh/kWp and 1031 kWh/kWp with an average of 984 kWh/kWp for 5 years.

Electricity consumption of residential buildings was derived from measurements by a Dutch distribution system operator and are publicly available online [33]. From this dataset, 48 demand patterns were selected with different dwelling types for 2013. Measured electricity consumption of 42 commercial buildings, mainly offices, was selected for 2013. Both datasets contains measurement data with a 15 min interval. No data of 2012 and between 2014 and 2016 were available, thus the consumption data of 2013 was used to fill the other four years. Weekdays and weekend days of the missing years were matched with the data of 2013. Heat demand of the buildings was not provided by electricity, therefore reducing the influence of ambient temperature on the electricity consumption. The residential and commercial demand patterns were used in a previous study [34]. All demand patterns were linearly interpolated to a 5 min interval to have a similar timestep as the PV yield pattern. Distributions of annual energy consumption of demand patterns are shown in Fig. 2. Mean values of the distributions are indicated by the dotted lines. Residential consumption has a significantly lower mean (3.4 MWh) compared to commercial consumption (430 MWh). Median electricity demand of 3.3 MWh and 270 MWh were found for residential and commercial systems respectively.

Prices for providing negative or positive FRR were obtained from the Dutch TSO TenneT. These prices are published online and record the minutely settlement prices for negative or positive FRR provision [35]. The time steps of the price data were reduced to a 5 min interval by taking the average of each 5 min. Distributions of negative and positive frequency restoration reserve prices for 2015 and 2016 are shown in Fig. 3. The prices of feasible negative FRR provision are indicated by a blue arrow and positive FRR provision by a green arrow. These areas are feasible for residential systems in the reference scenario.

## 2.4. Performance indicators

We used a set of technical and economic performance indicators to assess and compare the impact of the dispatch strategies. The parameters were calculated over the economic lifetime of the PV-battery systems.

### 2.4.1. Technical performance indicators

The contribution of the BESS for PV self-consumption is quantified using the self-consumption contribution ratio (SCCR). This is the share of PV produced power that is used to charge the battery energy storage ( $P_{B \text{ from PV}}$ ). The SCCR can be calculated for the SCO, PSCN and PFRN strategies. No energy from the battery is exported to the grid in these strategies and all energy charged in the battery is accounted as self-consumed energy. The PV power produced and the PV power charged to the battery storage were aggregated for a given time period, from the first timestep ( $t = 1$ ) until the last timestep ( $t_{\text{end}}$ ), see Eq. (4).

$$\text{SCCR} = \frac{\sum_{t=1}^{t_{\text{end}}} P_{B \text{ from PV},t} \cdot \Delta t}{\sum_{t=1}^{t_{\text{end}}} P_{\text{PV},t} \cdot \Delta t} \quad (4)$$

The share of battery storage capacity that was used to provide FRR is defined by the frequency restoration reserve storage ratio (FRRSR), i.e. the share of battery throughput used for FRR provision of the total battery throughput. The electricity provided for FRR consists of the power for positive and negative supply for each timestep. The total battery throughput consist of the energy charged and discharged by the battery inverter, see Eq. (5).

$$\text{FRRSR} = \frac{\sum_{t=1}^{t_{\text{end}}} (P_{\text{pos}} + P_{\text{neg}}) \cdot \Delta t}{\sum_{t=1}^{t_{\text{end}}} P_{B \text{ inv},t} \cdot \Delta t} \quad (5)$$

The storage use ratio (SUR) gives an indication of the share of time that the BESS was used. It is defined as the ratio between the time were the battery inverter load is not zero and the total time ( $t$ ), see Eq. (6).

$$\text{SUR} = \frac{\sum_{t=1}^{t_{\text{end}}} t, P_{B \text{ inv}} \neq 0}{\sum_{t=1}^{t_{\text{end}}} \Delta t} \quad (6)$$

Battery degradation affects the battery storage capacity and was therefore determined for each year. Battery degradation consists of calendric degradation ( $D_{\text{cal}}$ ) and cycle degradation ( $D_{\text{cyc}}$ ), see Eq. (7). The calendric degradation depends on the lifetime ( $L_{\text{cal}}$ ), which is the time period until 80% of the battery capacity diminishes due to calendric degradation. The cycle degradation depends on the total number of full cycle equivalents (FCE) until 80% of the battery capacity diminishes due to cycle degradation ( $N_{\text{FCE}}$ ). Rain-flow counting method was used to determine the number of cycles and the depth of discharge (DOD) [36]. A curve was used with the FCE for each DOD, based on parameters given in previous studies [22,37]. This curve was used to convert each cycle to a corresponding FCE. The corresponding FCE was aggregated from the first time step until the last time step of a year. The cycle degradation was found by dividing the number of FCE of the specific year by the total number of FCE used, see Eq. (7). The battery capacity reduction caused by calendric and cycle degradation was subtracted from the battery capacity of the previous year to determine the capacity of the following year.

$$D_{\text{cal}} = \frac{1-0.8}{L_{\text{cal}}} \quad (7a)$$

$$D_{\text{cyc}} = (1-0.8) \cdot \frac{\sum_{t=1}^{t_{\text{end}}} \text{FCE}_t \cdot \text{DOD}_t}{N_{\text{FCE}}} \quad (7b)$$

$$D_{\text{BESS}} = D_{\text{cal}} + D_{\text{cyc}} \quad (7c)$$

### 2.4.2. Economic performance indicators

The annual cash flows of a PV-battery storage system consists of two main components. The first component are storage cash flows related to the electricity tariffs ( $CF_{\text{ET}}$ ). The second component are storage cash flows related to provide FRR ( $CF_{\text{FRR}}$ ).

The electricity bought from and sold to the electricity grid reduces with the usage of a PV-battery system compared to a PV system without storage. The storage cash flows related to the electricity tariffs depends on the difference between the electricity cost of a PV system without battery and a PV system with a battery. These depend on the difference in bought electricity ( $E_{\text{buy}}$ ) and sold electricity ( $\Delta E_{\text{sell}}$ ) between a PV system and a PV-battery system. The bought electricity difference is the electricity bought by a PV system ( $E_{\text{buy PV}}$ ) minus the electricity bought by a PV-battery system ( $E_{\text{sell PV-B}}$ ). The sold electricity difference is the

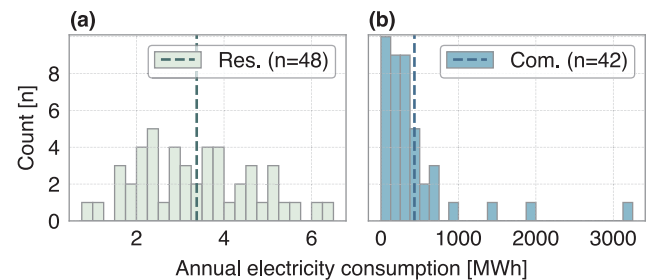
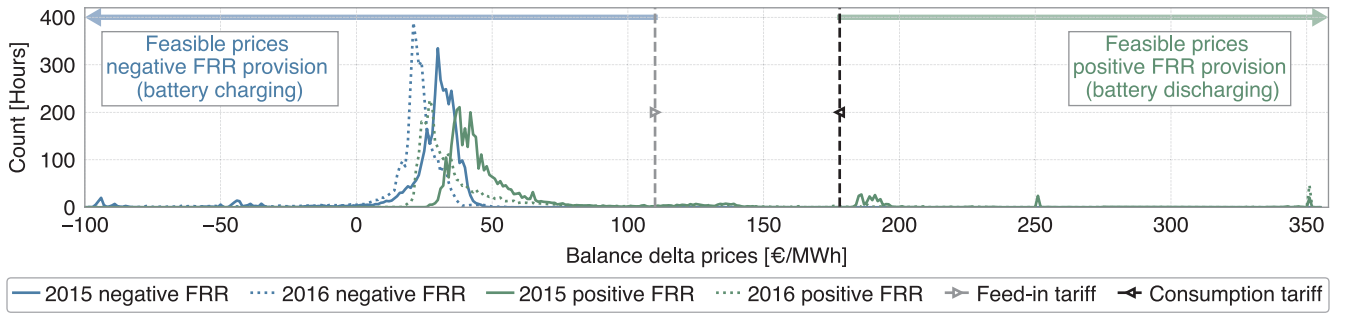


Fig. 2. Annual electricity consumption for residential (a) and commercial (b) systems used in this study are shown in a histogram. Mean values of the distributions are indicated by the dashed line. Histogram bins of 250 kWh for residential and 125 MWh for commercial systems were used.



**Fig. 3.** Distribution of balance delta prices for positive and negative secondary reserve provision for 2015 and 2016. A step size of 1 €/MWh was used. Note that there are prices observed which are out of the horizontal axis range. Feasible prices for positive provision are illustrated by the green arrow and for negative provision by the blue arrow. The prices are for the residential systems in the reference scenario. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

electricity sold by a PV system ( $E_{\text{sell PV}}$ ) minus the electricity sold by a PV-battery system ( $E_{\text{buy PV-B}}$ ). The value of the bought electricity depends on the consumption tariff and the value of sold electricity on the feed-in tariff. The cash flows related to electricity tariffs is determined by the value of bought electricity minus the value of sold electricity, see Eq. (8).

$$\Delta E_{\text{buy}} = E_{\text{buy PV}} - E_{\text{buy PV-B}} \quad (8a)$$

$$\Delta E_{\text{sell}} = E_{\text{sell PV}} - E_{\text{sell PV-B}} \quad (8b)$$

$$CF_{\text{ET}} = (\Delta E_{\text{buy}} \cdot \pi_{\text{cons}}) - (\Delta E_{\text{sell}} \cdot \pi_{\text{feed-in}}) \quad (8c)$$

The storage cash flow related to the provision of frequency restoration reserves is the difference between the cash flow from positive FRR provision and from negative FRR provision. We assume a mandatory provision, hence both the positive and negative prices are remunerated within 15 min. The cash flow from positive FRR depends on the provided energy and price of positive FRR of each timestep. The cash flow from negative FRR depends on the subtracted energy and price of negative FRR of each timestep, see Eq. (9).

$$CF_{\text{FRR}} = \left( \sum_{t=1}^{t_{\text{end}}} P_{\text{pos},t} \cdot \pi_{\text{pos},t} \cdot \Delta t \right) - \left( \sum_{t=1}^{t_{\text{end}}} P_{\text{neg},t} \cdot \pi_{\text{neg},t} \cdot \Delta t \right) \quad (9)$$

The battery storage investment ( $I_{\text{BESS}}$ ) includes costs of the storage system ( $C_{\text{B store}}$ ), BOS cost ( $C_{\text{B BOS}}$ ) and EPC cost ( $C_{\text{B EPC}}$ ). The battery storage cost are scaled with the size of the battery storage capacity ( $S_{\text{B store}}$ ), whereas the other cost are scaled with the battery inverter rating ( $S_{\text{B inv}}$ ), see Eq. (10).

$$I_{\text{BESS}} = (C_{\text{B store}} \cdot S_{\text{B store}}) + ((C_{\text{B BOS}} + C_{\text{B EPC}}) \cdot S_{\text{B inv}}) \quad (10)$$

The annual storage revenue ( $R_{\text{BESS}}$ ) are the revenues that can be allocated to the battery storage system. This is the sum of cash flows minus the annual operation and maintenance costs (O&M), see Eq. (11). O&M costs of the battery systems were calculated by using a cost factor ( $f_{\text{B OM}}$ ) which was multiplied with the battery system investment costs.

$$R_{\text{BESS}} = CF_{\text{ET}} + CF_{\text{FRR}} - (I_{\text{BESS}} \cdot f_{\text{B OM}}) \quad (11)$$

The simple payback period (PBP) is an indication of the time period required to recover storage investment. The PBP was found by selecting the year ( $y$ ) where the cumulative cash flow (CCF) is identical to zero. A maximum time period of 50 years was assessed to find the simple PBP, see Eq. (12).

$$CCF_y = \sum_{y=0}^{y=50} I_{\text{BESS},y} - R_{\text{BESS},y} \quad (12a)$$

$$\text{PBP} = \{y \text{ where } CCF_y = 0\} \quad (12b)$$

The profitability index (PI) gives a perspective of the value and risk of the battery storage investment. The profitability index is defined as

the present value per € invested. The present value includes the future risk and return in the current value of a project. This value is found by the sum of the annual total revenues for each year minus the investment cost for each year discounted by the rate ( $r$ ) over the economic lifetime ( $L_{\text{econ}}$ ). Only initial investments are included at the start of a project, see Eq. (13).

$$PI = \frac{\sum_{y=0}^{L_{\text{econ}}} \frac{R_{\text{storage},y}}{(1+r)^y}}{I_{\text{BESS}}} \quad (13)$$

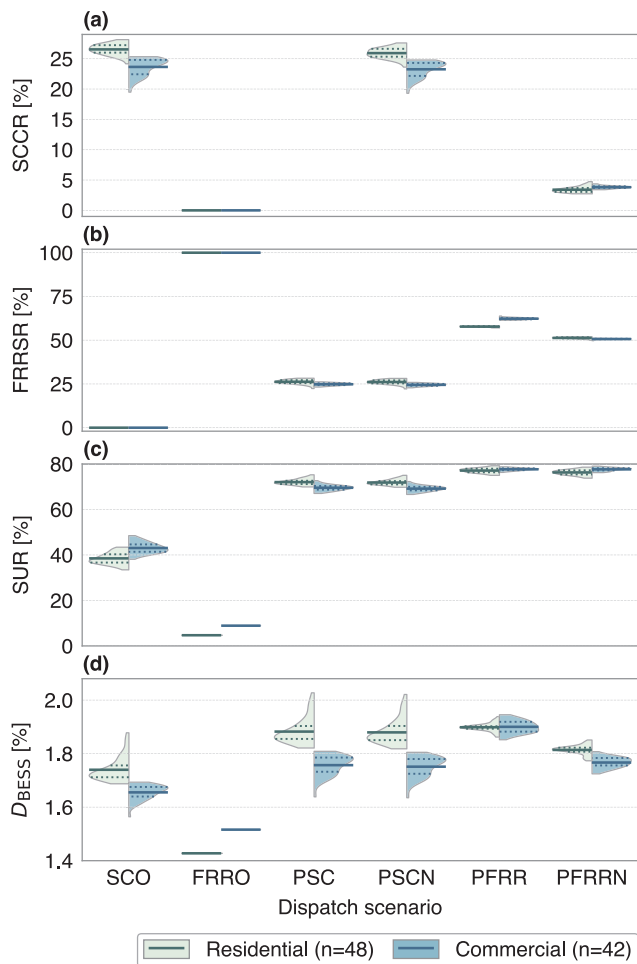
### 3. Technical assessment

The impact of the dispatch strategies on the technical performance indicators is shown using a violin plot in Fig. 4. Violin plots combine the box-whisker plot with a density plot and provide a quick indication of the obtained results [38]. Residential PV-battery systems are in all plots shown on the left side of the violin and commercial systems on the right side. Mean values of the distribution are indicated by the solid line and the 25% and 75% percentile by dotted lines. The systems performance indicators are annual values, averaged over the systems lifetime. All results are given for each MWh of annual consumption, enabling a comparison of the systems.

#### 3.1. Self-consumption contribution rates

SCCRs were determined for three out of six strategies. No PV energy was used for battery charging in the SCO strategy, thus no increase in PV self-consumption occurred. The SCCRs were not calculated for the PSC and PFRR strategy, because positive FRR was provided in these strategies. Consequently, not all energy stored from the PV system can be counted as self-consumption for these strategies. The SCO strategy shows an average SCCR of 26.5% for residential systems and 23.6% for commercial systems. A small decrease in average SCCR for residential and commercial systems is seen between the SCO and the PSCN strategy of  $\approx 0.5\%$ . The PFRRN strategy shows a small SCCR of 3.4% for residential and 3.8% for commercial systems. In this strategy, it occurs more often that the battery inverter was used to provide negative FRR than that it was used to charge excess PV electricity. In addition, less battery capacity is available to charge PV energy for moments when provision of negative FRR was not feasible. Both lead to a reduction in self-consumption of  $\approx 23.1\%$  point for residential and  $\approx 22.1\%$  point for commercial systems.

Residential systems have less overlap of energy consumption and PV production than commercial systems. Therefore, more energy can be shifted by storage with residential than commercial systems. This results in a higher SCCR for residential systems in the SCO and PSCN dispatch strategies. In addition, a higher SCCR in the PFRRN strategy is observed for commercial systems than for residential systems.



**Fig. 4.** Influence of the dispatch scenarios on the self-consumption contribution rate (a), frequency restoration reserve storage ratio (b), storage use rate (c) and battery degradation (d) for PV-battery systems shown using violin plots. The values are the annual average values over the lifetime of the system. Residential systems are shown on the left side of the distributions and commercial systems on the right. PV-battery system design parameters are given in Table 1. Mean values of distributions are indicated by solid lines, and the 25% and 75% percentiles by dotted lines.

Commercial systems have a lower feed-in tariff and thus lower prices for negative FRR provision compared to residential systems. Therefore, more negative FRR could be provided by commercial systems. Subsequently, the battery is discharged more often and thus more storage capacity is available to increase PV self-consumption.

### 3.2. Frequency restoration reserve storage ratio

The average FRRSR of the PSC and PSCN strategies are around 26% for residential and 25% for commercial systems. The small FRRSR difference between the PSC and PSCN strategies indicate a minor impact of the positive FRR provision. In these strategies, battery storage is mainly charged by surplus PV energy, which restricts the amount of positive FRR provision.

The occurrence of feasible positive provision is much lower than feasible negative provision (see Fig. 3). Therefore the added FRRSR by positive FRR provision is lower than the negative provision. A larger difference between the PFRR and PFRRN strategies is observed for commercial than for residential systems. The consumption tariff of commercial systems is significantly lower than for residential systems, resulting in a larger possibility of positive FRR provision for commercial systems. The PFRR strategy has a higher average FRRSR of  $\approx 6.4\%$  point

for residential and  $\approx 13.3\%$  point for commercial systems, compared to the PFRRN strategy. This difference is mainly caused by the additional positive FRR supply. However, FRRSR are in the PFRRN strategy slightly larger for residential systems than for commercial systems, and this is related to the difference in feed-in tariff.

### 3.3. Battery storage use and degradation

The use of the battery storage systems in the SCO strategy is on average 38.5% for residential and 43.1% for commercial systems. Commercial systems have a better overlap of PV production and energy consumption, hence battery storage is charged at a lower capacity during daytime for commercial than for residential systems. This results in a 4.6% point higher SUR for commercial systems. The SUR is significantly increased when FRR provision and self-consumption enhancement are combined. Mean SUR in the PSC and PSCN dispatch strategies are 71.9% for residential and 69.4% for commercial systems. The PFRR and PFRRN strategies show a SUR around 77% for residential and 4.6% for residential and 10.5% for commercial systems.

The sum of SURs from the SCO with the FRRO strategy is lower than for dispatch strategies that combine both applications. Thus, the battery is used more often when self-consumption enhancement is combined with FRR provision than the sum of each application individually. This is caused by two effects. First, electricity that is originally charged by negative FRR provision is delivered to the building. This increases the SUR for the PSC and PSCN strategies. Second, electricity that is produced by PV energy is used as positive FRR provision. This increases the SUR even more, as shown in the PFRR and PFRRN strategies.

Overall, annual battery degradation is between 1.4% and 2%, but it varies for different dispatch strategies. Low degradation values are observed in the FRRO strategy and high degradation values in the PFRR strategy. Relatively high degradation values of residential system are observed for the PSC and PSCN strategies, which indicate a higher frequency of charge and discharge cycles. Low degradation values in the FRRO strategy are caused by the low utilization of the battery storage. Battery degradation is higher for residential than for commercial systems, except in the PFRR strategy. This strategy has a higher provision of FRR by commercial systems, leading to higher degradation values.

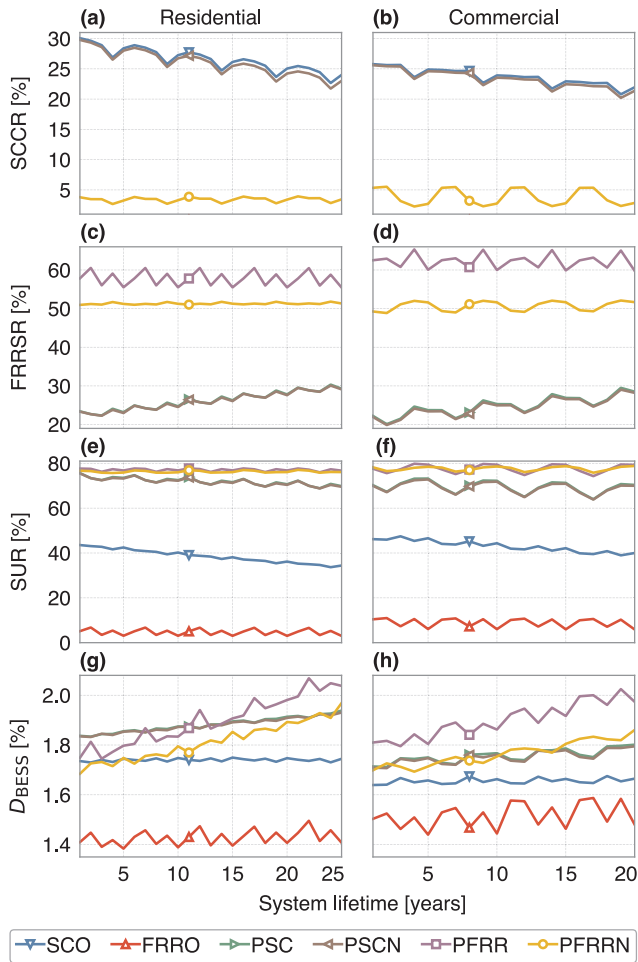
The electricity time-of-use influences the moment that surplus PV energy is stored or discharged, which varies for each demand pattern. The feasible provision of FRR is less dependent on the demand pattern, but more on the state of charge of the battery. Consequently, all system performance indicators show a larger distribution range for strategies that prioritize PV self-consumption. The distribution range of residential and commercial systems decreases with more FRR provision. Systems in the FRRO strategy are operating solely based on the FRR market prices, which are similar for all systems, so no distribution is seen.

### 3.4. Technical annual variations

Annual mean values for the technical system parameters are presented to provide insights in the yearly variation of the PV-battery systems, see Fig. 5. The annual variation of the SCCR and the FRRSR are caused by the variation in PV production, battery storage capacity and FRR prices.

Residential SCCR shows an annual variation of around 8% point for the SCO and PSCN strategies and 1% point for the PFRRN strategy. Commercial SCCR shows a lower variation in the SCO and PSCN strategies of around 5% point, yet a higher variation in the PFRRN strategy of 3% point is observed. PV energy production is reduced over time caused by the PV system degradation. This increases the share of direct consumed PV energy, but reduces the share of PV energy that can be stored. Consequently, less PV energy is stored and SCCR decreases over



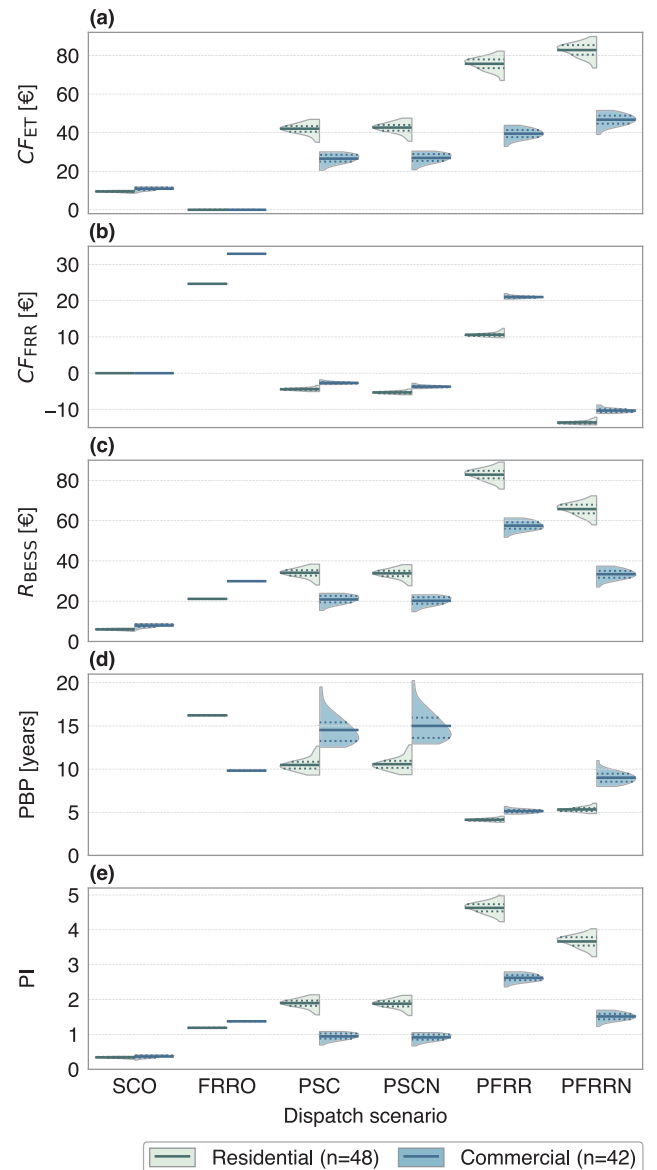


**Fig. 5.** Mean annual distribution values for self-consumption contribution rate (a & b), frequency restoration reserve storage ratio (c & d), storage use rate (e & f) and battery degradation (g & h). The left columns shows residential systems (a, c, e & g) and the right columns commercial systems (b, d, f & h). PV-battery system design parameters are given in Table 1.

lifetime. Also, battery storage capacity decreases over lifetime due to degradation. This decreases the PV energy that can be stored and used on later moments, which reduces the SCCR even more. This effect is not visible in the PFRRN strategy, due to the prioritization of FRR provision is the initial SCCR already limited.

Commercial systems provide more negative FRR than residential systems, thus have a higher annual variation in SCCR and FRRSR. The PSC and PSCN strategy have an increase of FRRSR over time caused by the reduction of the battery capacity. As a result of this reduction, a SOC of 0% due to discharge of electricity delivered to a building is achieved more often. Also a SOC of 100% due to the charge of PV energy is realized more frequently. Consequently, the assessment of feasible FRR provision in the PSC and PSCN strategies will occur more often and more FRR is provided. Provision of FRR was already maximized for the PFRR and PFRRN strategies which show a constant FRRSR over time.

The reduction in battery capacity results in more moments that the battery capacity is saturated, in which reduces its moments were a battery can be charged. The fluctuation of request for PV charging is smaller than request of negative FRR provision. Besides, PV energy is charged during daytime, whereas negative provision fluctuates over the course of the day. Hence, the SCO strategy shows a strong decrease in SUR, whereas the PSC and PSCN strategies show a weaker decrease. A minor reduction of SUR is seen for dispatch strategies that prioritize self-consumption enhancement. Annual battery degradation increases



**Fig. 6.** Influence of the dispatch scenarios on the annual average cash flow from electricity tariffs (a), annual average cash flow from frequency restoration reserve provision (b), annual average storage revenue (c), payback period (d) and the profitability index (PI) for PV-battery systems shown using violin plots. PV-battery system design parameters given in Table 1. Mean values of distributions are indicated by solid lines, and the 25% and 75% percentiles by dotted lines.

over time for all dispatch strategies, except the self-consumption only strategy. The power charged and discharged for FRR provision stays constant over time but the storage capacity decreases. Therefore storage cycle depths and consequently battery degradation both increase.

#### 4. Economic assessment

The impact of BESS dispatch strategies on the economic performance indicators is presented in Fig. 6. The cash flow from the electricity tariffs, cash flow from FRR provision and the storage revenues are annual averaged values over the lifetime of the systems.

##### 4.1. Annual cash flows and storage revenue

The cash flow obtained with the electricity tariffs for the SCO strategy are on average  $\approx \text{€}9$  for residential and  $\approx \text{€}11$  for commercial

systems. These cash flows increase significantly when negative FRR is provided because less electricity is bought with the consumption tariff. The PSC and PSCN dispatch strategies have cash flows of €42 and €27 for residential and commercial systems respectively. Prioritizing FRR provision before self-consumption increases the cash flow even more. Yet, the cash flow from the electricity tariffs are higher for providing only negative FRR than when both positive and negative FRR are supplied. If positive FRR is provided, then electricity from the battery is used for positive FRR provision instead of using it for the electricity demand of the building. Thus, more electricity is bought which reduces these cash flows related to the electricity tariffs.

The cash flows related to FRR provision are only positive in the FRRO and PFRR strategies. Largest cash flows from FRR are seen for the FRRO strategy, since all negative FRR provision is sold back as positive FRR provision. These are €25 for residential and €33 for commercial systems. The PFRR strategy has a higher cash flow from positive FRR provision than costs from negative FRR provision. This results in a net cash flow for FRR provision of €11 and €21 for residential and commercial systems respectively. The consumption tariff of commercial systems is lower than for residential system. Hence, more moments in time occur for commercial systems for which a positive FRR is feasible. Therefore, the cash flow from commercial systems is ≈€10 higher than for residential systems in the PFRR strategy. The PFRRN strategy shows the lowest cash flows, yet has the largest reduction of electricity that is bought with the consumption tariff.

Highest storage revenues are observed in the PFRR strategy with €83 for residential and €58 for commercial systems. Lowest revenues are made with self-consumption only, of €6 and €8 for residential and commercial systems respectively. The difference in storage revenues between the SCO strategy and the other five strategies is an indication for the annual profit that can be obtained by operating on the frequency restoration reserve market. The largest differences are observed in the PFRR strategy of ≈€77 for residential and ≈€50 for commercial systems. Strategies that prioritize self-consumption (PSC & PSCN) have a lower differences of ≈€28 for residential and ≈€12 for commercial systems. The PSC strategy shows slightly higher storage revenue than the PSCN strategy due to the benefits of positive FRR provision.

Residential storage revenues of the FRRO strategy are smaller than the revenues obtained in the PSC and PSCN strategy, yet commercial systems show larger revenues. The lower consumption and feed-in tariffs of commercial systems result in more feasible moments for FRR provision, and higher revenues in the FRRO strategy. The variation of electricity time-of-use during the day for commercial systems is lower than residential systems. Subsequently, the distribution range of commercial systems is smaller than for residential systems.

#### 4.2. Investment attractiveness

Simple payback periods of the SCO dispatch strategy are larger than 50 years for residential systems and larger than 43 years for commercial systems so are not shown in Fig. 6. Payback periods are significantly lower for strategies that prioritize FRR provision. If self-consumption enhancement is prioritized before FRR provision, then PBP of residential systems is lower than commercial systems. The difference between the feed-in and consumption tariffs is larger for residential than commercial systems, resulting in larger benefits for PV self-consumption.

The profitability index value should be higher than 1 for an economically profitable investment. The PI in the SCO dispatch shows values smaller than 1 for residential and commercial systems, making the investment in battery storage not economically feasible. The FRRO strategy has higher PI for commercial than residential systems, thus the price points used for feasible FRR provision should be closer to commercial tariffs than for residential tariffs. The PI of residential systems is above 1 in the other four strategies, indicating a positive investment. Commercial systems show PI above 1 for all systems in the PFRR and

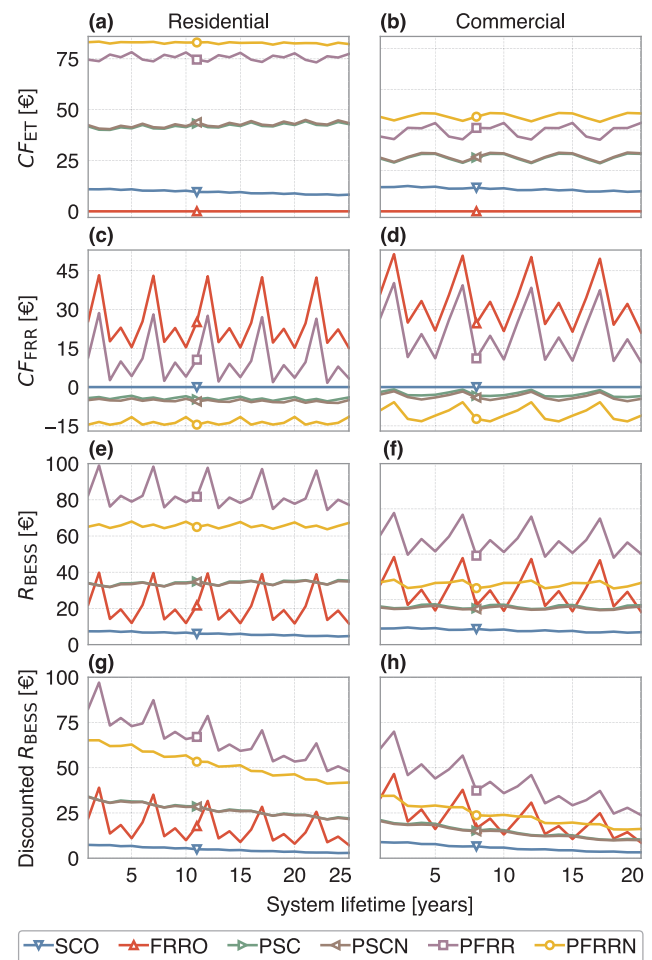


Fig. 7. Mean annual distribution values for cash flow from electricity tariffs (a & b), cash flow from frequency restoration reserve provision (c & d), storage revenue (e & f) and discounted storage revenues (g & h). Residential systems (a, c, e, & g) are shown on the left and commercial systems (b, d, f & h) are shown on the right. PV-battery system design parameters are given in Table 1.

PFRRN dispatch strategy, but for the PSC and PSCN strategies an average PI below 1 is observed.

It is remarkable that the simple PBP for the PFRR and the PFRRN strategies is lower for residential than for commercial systems, whereas the PI shows the opposite. This is caused by differences in economic assumptions made for the systems. Residential systems have an economic lifetime of 25 years and a discount rate of 2%, whereas commercial systems have a shorter economic lifetime of 20 years and a higher discount rate of 4%. The time period needed to recover the investments is shorter for commercial systems. Also the future value of the storage revenues decreases faster due to a higher discount rate. Both these effects result in a lower PI for commercial systems than residential systems.

#### 4.3. Economic variations

Annual mean values for cash flow from electricity tariffs, cash flow from FRR provision, storage revenue and discounted storage revenues are shown in Fig. 7. The SCO strategy shows a reduction of annual cash flow from electricity tariffs for residential and commercial systems over time. A reduction in self-consumption increases electricity costs (see Fig. 5). Residential systems can obtain more storage revenues for self-consumption than commercial systems. Hence, the drop in revenue is larger for residential than commercial systems. The PSC and PSCN strategies show that losses due to the reduction of self-consumption are

compensated by the additional benefits of negative FRR provision. Hence, a slight increase in cash flow from electricity tariffs is observed. Besides, more revenue in providing negative FRR is obtained by residential than commercial systems. As a result, the increase in cash flow from electricity tariffs is larger for residential than for commercial systems.

The cash flows from FRR provision show large fluctuations for the FRRO and PFRR strategies, caused by price fluctuation of positive FRR provision. A slight decreasing trend is seen over time due to reduced battery capacity. The FRR cash flows over time are constant for the PFRRN strategy while the PFRR revenues show small decreases. Less positive reserves can be provided over time due to the reduced battery capacity. Commercial systems supply more positive FRR and thus show a larger variation than residential systems. The storage revenues decrease in all dispatch strategies with the SCO strategy as being the most severe. The discount rate for commercial systems is twice as high as for residential systems. Consequently, the discounted storage revenues show a steeper decrease for commercial than residential systems. The impact of the battery degradation combined with a discount rate results in  $\approx 60\%$  decrease of storage revenue in the SCO strategy.

## 5. Sensitivity analysis

### 5.1. Reference parameters sensitivity

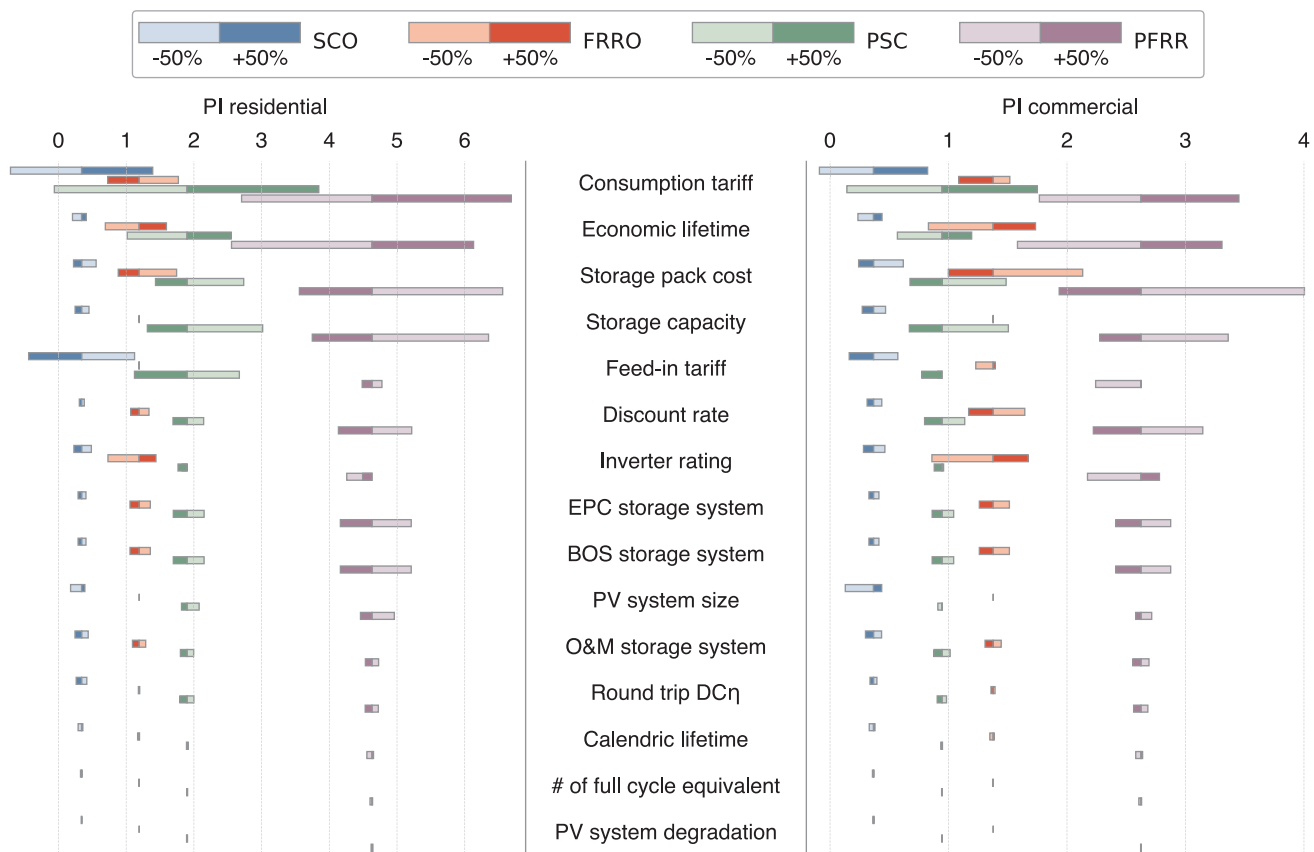
A sensitivity study of the system reference parameters was conducted on the PI for the SCO, FRRO, PSC and PFRR dispatch strategies. The PSCN and PFRR dispatch strategies are excluded in the sensitivity study, because these options are less realistic to implement. We varied all reference parameters between  $+50\%$  and  $-50\%$  of the initial

reference value, see Table 1. The sensitivity of the profitability index for the SCO, FRRO, PSC and PFRR dispatch strategies are presented in a tornado diagram in Fig. 8. The impact of each PV-battery system parameter varies per dispatch strategy. Therefore, we could not rank the parameters according to sensitivity range.

Residential systems show no feasible investment in the SCO strategy with most system parameters. The SCO strategy only becomes economically profitable when the consumption tariff is increased or the feed-in tariff is reduced. The FRRO strategy requires a reduction of consumption tariff, storage cost or capacity to increase the profitability above 1. An increase in economic lifetime or inverter rating could also be a possibility to improve the PI substantially. If the economic lifetime or the consumption tariff is reduced than the investment attractiveness is lost for the PSC strategy. The PFRR strategy shows PI of higher than 1 for all investigated parameters. Commercial systems show no PI value above 1 in the SCO strategy. In contrast to residential systems, commercial systems show a higher certainty for the FRRO strategy to obtain a positive investment. The PFRR dispatch strategy only shows PI values larger than 1, similar as for residential systems.

Large influences of consumption tariff are seen on all dispatch strategies, especially for the strategies that include enhancement of self-consumption. The feed-in tariff shows a lower influence on the FRRO and dispatch strategies that prioritize frequency restoration reserve provision for residential systems. For commercial systems, an increase in feed-in tariff in the FRRO and PSC strategies results in higher PI, whereas in the other strategies a reduction on PI is observed. More details and explanations on the sensitivity of electricity tariffs and FRR prices are given in Section 5.3.

The sensitivity of battery storage capacity and battery inverter rating are parameters that are highly affected by the used dispatch



**Fig. 8.** Sensitivity of the PV-battery system parameters on the profitability index of residential and commercial systems. The lighter colours indicate the  $-50\%$  values whereas the darker colours show the  $+50\%$  values. Each system indicators shows from top to bottom the SCO, FRRO, PSC & PFRR battery storage dispatch strategies. Note that the PV-battery system parameters are not ranked on range of sensitivity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

strategy. A reduction of battery storage capacity results in a larger decrease in self-consumption than in FRR provision. The enhancement of self-consumption is the main objective in the PSC strategy. Consequently, a larger impact of storage capacity than storage pack cost is seen for this strategy. The other strategies show a larger impact of storage pack cost. A decrease in inverter rating reduces the cost of an inverter, but also reduces the FRR power that can be provided. In the SCO strategy, the benefit of reduced inverter cost is higher than the loss of power provision. Strategies which provide positive FRR provision show the opposite, especially visible for commercial systems.

An increase in PV system size results in more excess PV production and consequently more moments when the battery can be charged to enhance self-consumption. Therefore the PI in the SCO strategy increases with larger PV systems. However, strategies that provide FRR show a reduction of PI with an increased PV system. In these strategies, more storage capacity will be used to store excess PV energy. Consequently, less storage capacity is available for FRR provision which reduces the PI.

The operation and maintenance cost is the only parameter that has a similar impact on the PI for all strategies. These costs are fixed for the system, therefore not dependent on the strategy used to charge or discharge the battery. The influence of round trip battery efficiency and PV system degradation is found to be minimal on the PI of the systems with all dispatch strategies. The impact of calendric lifetime and the number of full cycle equivalents is also limited. More details and clarifications on the sensitivity of battery degradation parameters are given in Section 5.4.

## 5.2. Storage capacity and inverter rating

The sensitivity of battery storage and relative inverter rating was investigated in detail with the reference scenario. We used contour plots to analyse the combined effect of these influences on four dispatch strategies which are presented in Fig. 9. Battery storage capacities were varied with steps of 0.1 kWh and relative inverter values with steps of 0.1 kW. Residential systems are shown in the top graphs and commercial systems in the bottom graphs. The red points indicate the maximum PI within the investigated range of battery storage and inverter ratings.

The SCO strategy shows only profitability indexes below 1 for residential and commercial systems. The PI in the FRRO strategy is mainly depending on the relative inverter rating. A higher inverter rating can deliver more power and thus increases the PI. The PSC

dispatch strategy shows that a larger inverter does not automatically increase the PI. A larger inverter can charge and discharge a battery faster. Consequently, more energy can be delivered for the FRR market with equal battery storage capacity. Yet, a reduction of PI is observed in the PSC strategy. Larger inverter ratings will also increase the charged surplus PV electricity or the discharged electricity to the building. Hence less battery capacity is available to provide FRR and also the PI is reduced. The PFRR strategy shows a significantly increase in PI for residential as well commercial systems. An increase in storage size results only in higher PI if inverter ratings increase as well.

A lower inverter rating was found when no FRR was provided. The SCO shows an optimal inverter size of 0.2 kW for residential systems and 0.3 kW for commercial systems. The strategies that provide FRR have an inverter rating of 0.9 or 1. The optimal battery storage size is for each strategy 0.1 kWh per MWh of electricity consumption, except for the commercial FRRO strategy. Commercial systems can provide more positive reserves than residential systems due to the lower price point used. Hence commercial systems benefit more from a larger storage capacity.

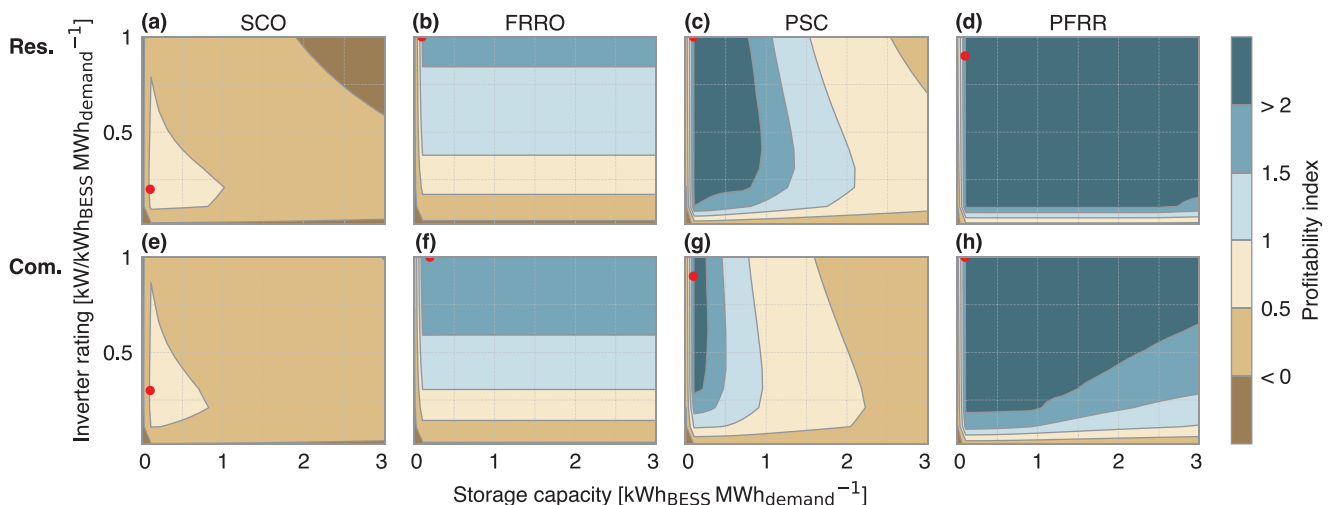
## 5.3. Electricity tariffs and FRR prices

Future electricity tariffs and frequency restoration prices are highly uncertain due to changes in policy or technology. Therefore, the sensitivity of the annual price variation on dispatch strategies was analysed using four price scenarios.

- P1 Consumption tariff was varied, feed-in tariff and FRR prices were kept constant.
- P2 Feed-in tariff was varied, consumption tariff and FRR prices were kept constant.
- P3 Consumption and feed-in tariff were kept constant and FRR prices were varied.
- P4 Both tariffs and FRR prices were simultaneously varied.

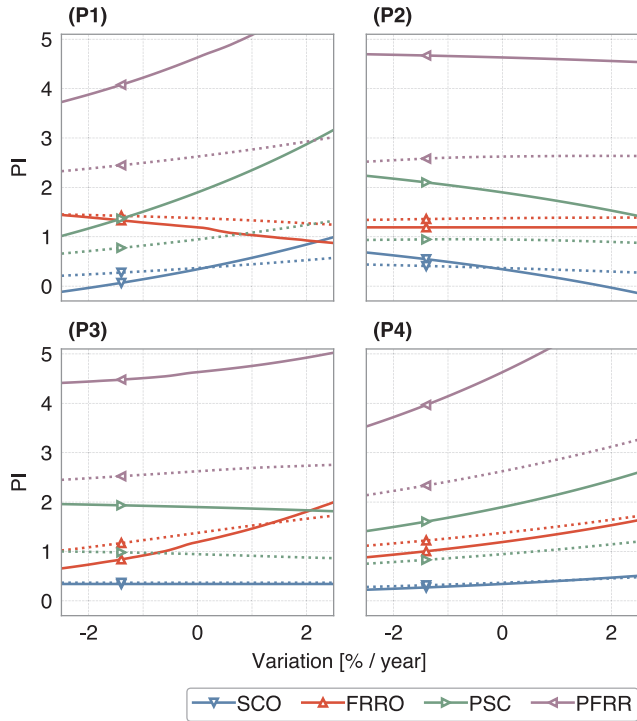
The sensitivity of dispatch strategies for each price scenario is presented in Fig. 10. The annual variation was modelled between  $-2.5\%$  and  $+2.5\%$  in steps of  $0.1\%$ /year.

Price scenario 1 shows an increase in PI for all strategies, except the FRRO strategy. The value of self-consumed energy and consequently storage increases with higher consumption tariffs. Residential systems have a higher initial consumption tariff, thus a larger increase in



**Fig. 9.** Influence of battery storage and relative inverter ratings of four strategies, indicated above the graphs. Mean values of the residential systems are shown at top graphs (a, b, c & d, indicated with Res.) and mean values of commercial systems are shown at the bottom graphs (e, f, g & h, indicated with Com.). The red points indicate the maximum profitability index within the system values of the sensitivity study. Other parameters are kept constant according to the reference PV-battery system scenario. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)





**Fig. 10.** Sensitivity of prices from electricity tariffs and secondary reserve provision for the four price scenarios on the profitability index of four strategies. The solid lines show the average value of residential systems and the dotted line shows averages of commercial systems.

absolute values and higher PI. Also the price difference between consumption tariff and feed-in tariffs is larger for residential systems than for commercial systems. Consequently, the impact of electricity price variation is higher for residential systems. A higher consumption tariff results in reduced moments for feasible provision of positive FRR. The FRRO strategy shows a steeper decrease of the PI for residential than for commercial systems. This is a result of the larger absolute difference of price points for residential systems.

The P2 scenario shows a decreasing profitability index with increasing annual variation of the feed-in tariff in all strategies except in the FRRO strategy and in the commercial PFRR dispatch strategy. The

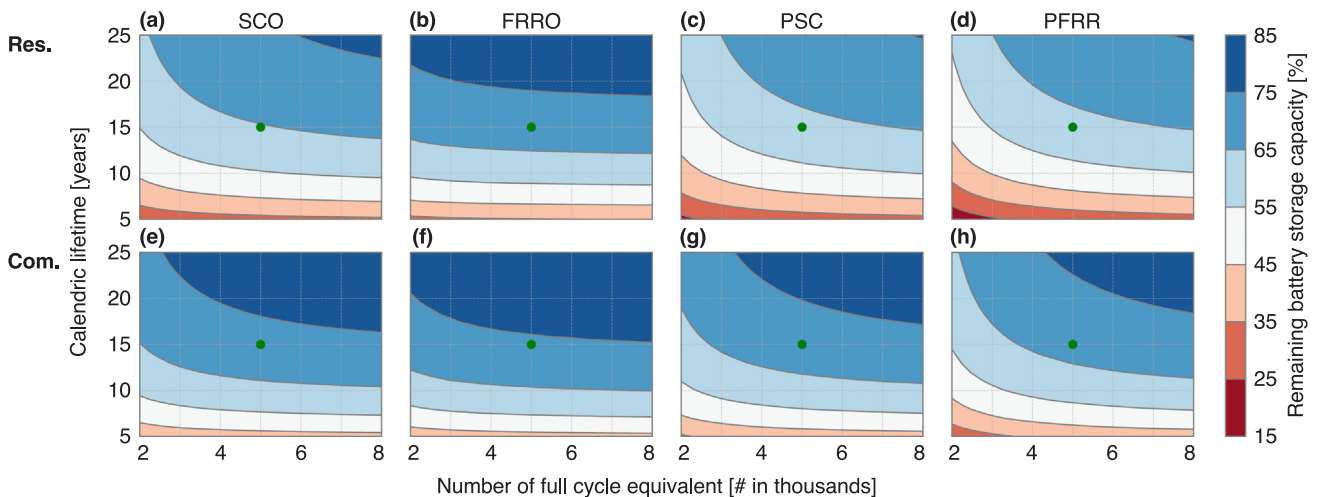
increase of feed-in tariffs has two main effects. First the difference between the consumption tariff and the feed-in tariff is reduced. Consequently the value of self-consumed energy and stored energy lowers, resulting in a reduced PI. Second, the increase of feed-in tariffs leads to more moments when negative provision becomes feasible. Therefore, less energy is bought with the consumption tariff, increasing the PI. Residential systems have a larger difference between the consumption tariff and the feed-in tariff than commercial systems. Also the feed-in tariff is larger for residential systems. Hence, the first effect is larger for residential systems, and the second effect is bigger for commercial systems. The commercial PFRR is the only strategy in which the benefits of more negative FRR provision is larger than the loss in self-consumption.

Price scenario 3 shows different trends between the dispatch strategies. The PSC dispatch strategies show a decrease of PI with increasing annual variation. Higher prices reduce the feasibility of negative FRR provision and more energy must be bought from the grid to fulfil the local energy demand. The PSC strategy has a lower battery storage use ratio due to the prioritization of self-consumption, see Fig. 4. Hence, the likelihood to provide positive FRR is lower than to provide negative FRR. Thus, the benefits of the higher positive FRR prices are lower than the loss of the negative FRR prices. This results in a decrease of PI in the PSC strategy. The FRRO and the PFRR show an increase in PI because more time moments occur when delivery of power for the FRR market becomes feasible. The influence of the variation of consumption and feed-in tariffs is larger than the influence of the FRR market prices, thus P4 shows an increase in PI for all strategies.

#### 5.4. Battery capacity degradation

A commonly heard concern is the influence of the calendric lifetime and the number of full cycle equivalents on battery capacity. Therefore, we assessed the influence of these parameters on the battery storage capacity that is remaining after the economic lifetime of the systems expires, see Fig. 11. The number of full cycles was varied with steps of 250 and the calendric lifetime with steps of 1 year. Remaining parameters were kept constant according to the reference scenario.

A larger range in storage capacity degradation is observed for the investigated battery degradation parameters. Between 17.5% and 83.3% of the battery capacity remains after the economic lifetime. The impact of calendric degradation decreases with a higher number of FCE. The economic lifetime of the commercial systems is 5 years shorter than



**Fig. 11.** Influence of the number of full cycle equivalent and the calendric lifetime on the remaining battery capacity after the economic lifetime of the systems expires. Mean values of the residential systems are shown at top graphs (a, b, c & d, indicated with Res.). The bottom graphs indicate the mean values of commercial systems (e, f, g & h, indicated with Com.). The green dot indicates the reference scenario. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 2**

Estimated number (in thousands) of reference battery systems participation before secondary reserve market saturation for residential and commercial systems for 2014.

	Residential ( $\cdot 10^3$ )		Commercial ( $\cdot 10^3$ )	
	Positive	Negative	Positive	Negative
FRRO	732	168	4.22	0.98
PSC	28,011	72	143	1.07
PSCN	–	71	–	1.07
PFRR	787	24	4.11	0.29
PFRRN	–	26	–	0.34

the residential systems. Consequently, the reduction in storage capacity is more severe for residential than for commercial systems.

When the reference battery degradation parameters would be changed to a calendric lifetime of 5 years and 2000 FCE, than a substantial capacity reduction would occur with all dispatch strategies. The remaining storage capacity in the SCO strategy would decrease from 64.5% to 27.6% for residential systems and from 72.6% to 37.2% for commercial systems. The revenue of storage decreases even more due to the discounting of the future revenues. Therefore, the impact of the battery degradation on the PI is less substantial than on capacity reduction. The average PI decreases from 0.34 to 0.22 for residential systems and from 0.37 to 0.28 for commercial systems.

Similar reductions in battery capacity are observed for the FRRO strategy, with a decrease from 69.8% to 32.6% for residential and from 73.7% to 38.6% for commercial systems. However, a smaller reduction in PI is observed, specifically from 1.19 to 1.14 for residential and 1.38 to 1.31 for commercial systems. Hence, the battery degradation has a significant lower impact on the profitability of the FRRO strategy than on the SCO strategy. Largest capacity reductions are observed for the PFRR strategy, of  $-44.5\%$  point for residential and  $-40.3\%$  point for commercial systems. Also a larger reduction is seen in PI of  $-0.24$  for residential and  $-0.13$  for commercial systems. These results are in agreement with results on the SUR presented in Section 3. The PSC strategy shows a small increase in PI for residential systems (0.04) due to the increased FRR provision over the lifetime. Commercial systems have a small reduction of  $-0.02$  because of lower benefits of negative FRR provision.

## 6. Discussion

This research assessed PV-battery systems that combine self-consumption enhancement with provision of frequency restoration reserves. We found that provision of FRR significantly increases storage revenues of PV-battery systems. The minimum feasible price for positive FRR provision and maximum feasible price for negative FRR provision show a large impact of the profitability on FRR provision.

### 6.1. Market assumptions

The largest uncertainty in our study is the use of historical negative and positive prices for frequency restoration reserve provision in our model. Perfect price forecasting was assumed which led to optimal PV-battery system benefits. However, FRR prices are difficult to predict since this market is designed to handle the unexpected variation between energy supply and demand [39]. This leads to higher financial risks. Voluntary contribution to the FRR market would significantly reduce these risks, but also reduces the obtained revenues. In our research the consumption and feed-in tariff were selected as price points for FRR provision, yet different price points could increase the revenues from FRR provision. Besides, positive and negative prices should always be selected in respect to each other [8]. We recommend additional research on the impact of these points for the profitability of FRR

provision.

Future market prices could significantly change with a higher share of renewable electricity production. The increase in wind and solar electricity generation capacities result in larger power input fluctuation on the grid. As a result, it is expected that demand for frequency restoration reserve will increase and a larger fluctuation of prices will occur [40]. This market behaviour could invite more actors to operate on the frequency control market, especially with a reduction in battery storage cost [41]. These new actors can cause an increase the supply of the FRR, which can eventually cause a decrease in FRR market prices. The modelling of market prices in not studied in great detail because there is a small number of actors and low revenues on this market. Hence, one of the major challenges is to improve the current models for FRR price and volume prediction.

The Dutch market size for providing positive FRR was 45.8 GWh and for negative FRR 167.7 GWh, for 2014 [42]. This market size limits the number of PV-battery storage systems that can provide FRR. We assessed the market potential by determining the number of systems that can be installed before the market saturates for 2014. The median of the demand patterns were selected, which are an annual energy consumption of 3.3 MWh and 270 MWh for residential and commercial systems, respectively. Furthermore, reference PV-battery system parameters were used (see Table 1). The number of systems (in thousands) for positive and negative FRR provision is shown in Table 2.

The number of systems that could provide positive FRR is an order of magnitude larger than the number that could provide negative FRR. This difference is related to the lower number of feasible moments to provide positive FRR. More residential storage system can enter the market than commercial systems. Around 300.000 residential PV systems were already installed before 2016 in the Netherlands [43]. If a battery storage system of 1 kWh is added for each kWp of installed PV system capacity, then the market for negative provision is already saturated. Therefore, it is important to take these limitations into account, especially so with a growing number of installed PV-battery storage systems.

An increase in electricity market prices, additional taxes or grid fees results in higher consumption tariffs for both residential and commercial systems. On the other hand, the feed-in tariffs for residential systems are currently dependent on subsidy policies for renewable energy generation. It is expected that these subsidies will be abolished and that the feed-in tariffs will drop. This will increase the value of self-consumed energy and benefits of energy storage. Other applications, such as electrical vehicles or heat pump systems could be used to provide balancing services. These applications could influence balancing costs [42,44]. European grid interconnections are increasing and cross border balancing markets are under development. This results in more connections between the international market and therefore a larger market is created for balancing reserves, which influences prices [45].

### 6.2. Implementation considerations

Normally, residential PV-battery storage systems are connected to a low voltage grid. The total power that can be provided to this grid or subtracted from this grid is limited by the capacity of the transformers connected to this grid. Aging of transformers is enhanced when the substation transports power to higher voltage networks [46]. Therefore, it is recommended to set limitations on the power capacity that can be used for FRR provision within a low voltage grid. Flexible limitations could be used when accurate knowledge about the power consumption within the local grid is available. Furthermore, planning and communication between district system operators and the active actors of storage systems is advised to prevent problems related to grid and transformer capacities. Research on the impact of providing FRR on the low voltage grid is recommended as a possible next step.

This research provides a first estimate on the monetary benefits for individual battery systems. However, the minimum bid size to trade on

the frequency restoration reserve market is 4 MW currently. Battery systems must be pooled to obtain the minimum bid size to comply with these market requirements. Therefore, an aggregator is required to combine the individual battery storage systems to comply with electricity balancing market rules. Larger pools provide more flexibility to trade on the electricity balancing market, but the individual revenue of the systems might decrease. Supplementary communication and battery management software can be required to deliver power to the market on the right moment. This information consists of availability of the battery system, the BESS state of charge and maximum inverter power. Aggregators could play an important role in providing this additional hardware and software. These communication requirements will add costs to a PV-battery system to be able to operate on the balancing market. Therefore the presented revenues from FRR provision could be overestimated. Besides, legal matters concerning battery ownership and taxation of revenues should be investigated before entering the market.

It is also possible to add a third application to the storage systems for even higher profitability. For example, BESS could shift the peak demand and therefore reduce the grid connection cost [47]. The benefits of each storage application and there interaction is highly recommended as future research.

## 7. Conclusion

This work is a first indication on possible additional benefits that residential and commercial PV-battery systems could have when they are combined to improve self-consumption and provide frequency restoration reserve to the balancing market. Six battery dispatch strategies were developed and assessed on technical and economic parameters. We used historical market prices data and energy consumption data of 48 residential and 42 commercial systems.

A small loss of 0.5% self-consumption rate is shown for strategies that prioritize self-consumption over provision of FRR. Larger reductions of around 3% are seen when FRR provision is prioritized. The battery use is significantly increased when both applications are used and even doubled when FRR provision is prioritized. The dispatch strategies have a minor impact on battery degradation. FRR provision as secondary storage applications increases annual revenue with  $\approx$ €28 for residential and  $\approx$ €12 for commercial systems for each kWh of storage capacity. Strategies that prioritize FRR provision before self-consumption enhancement have largest revenues of  $\approx$ €77 for residential and  $\approx$ €50 for commercial systems.

Electricity and FRR prices show a high influence on the profitability of the storage systems. Therefore developments in these prices should be estimated to examine an accurate profitability of BESS investments. The battery inverter ratings should be optimized with the battery storage size and the dispatch strategy to improve the profitability of the storage investment. Models to predict FRR prices and volume need increased accuracy. Limitations concerning future market developments and current electricity infrastructure should be analysed as a next research step.

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